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AGARD LECTURE SERIES No. 123

Aircraft Fire Safety

NORTH ATLANTIC TREATY ORGANIZATION

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AIRCRAFT FIRE SAFETY
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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Lecture Series No.123

AIRCRAFT FIRE SAFETY

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Propulsion and Energetics Panel and the Consultant and Exchange Programme of AGARD, presented on 7–8 June 1982 in Oslo, Norway: 10–11 June 1982 in London, UK and 15–16 June 1982 in Washington D.C., USA.

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Published May 1982

ISBN 92-835-1424-6

Printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London, W1P 1HD

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INTRODUCTION

by

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This Lecture Series No. 123 is sponsored by the "Propulsion and Energetics Panel (PEP)" and implemented by the "Consultant and Exchange Program" of AGARD.

Aircraft inherently possess a high fire and explosion hazard potential as a result of the large quantity of flammable fuel, other combustible fluids such as hydraulic and engine oils and the wide variety of solid combustible materials on-board. Application of fire protection engineering, constantly upgraded by lessons learned from aircraft fire incidents and mishaps, has led to the very effective control of the fire and explosion hazard in today's operational aircraft. This is manifested by the operational safety record which shows that by and large the overall residual fire risk is low. Several operational scenarios however, continue to receive attention with the objective of further enhancing aircraft and passenger survivability. For military aircraft these include the reduction of vulnerability to catastrophic fires and explosions associated with combat related, externally applied ignition sources such as ballistic rounds (incendiary and tracer), high energy fragments from explosive rounds, and directed energy weapons. On the civil transport side, which also relates to military transport aircraft, mishap experience has resulted in attention being focused on the in-flight interior cabin fire problem and the impact post crash fire situation. With respect to the loss of life attributable to fire effects, the latter two situations without question have been the principal recent contributors.

During the past 15 years particular emphasis has been placed on the enhancement of aircraft fire safety both from the combat survivability and everyday operational safety viewpoints. During this period AGARD PEP has contributed significantly in providing for international visibility and information exchange for aircraft fire safety matters. AGARD has sponsored two technical conferences in this area--the first in 1971 (Ref 1) and the second in 1975 (Ref 2), and subsequently supported Working Group 11 comprised of technical representatives from seven (7) NATO Countries which completed an in-depth cooperative analysis of aircraft fire problems in 1979 (Ref 3). The Working Group focused on transport type aircraft as a common or baseline point of departure and explored the broad spectrum of ramp, in-flight, and post-crash fire scenarios. For everyday operations, the post-crash fire scenario was identified as requiring the major attention.

In June 1980, the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee sponsored by the Office of Aviation Safety of the Federal Aviation Administration in the United States culminated 13 months of effort examining the factors affecting the ability of the aircraft cabin occupant to survive in the post-crash fire environment and the broad range of solutions available (Ref 4, 5 and 6).

This Lecture Series has been organized by AGARD to provide an up-to-date review of fire protection technology using the earlier analyses as the point of departure with the principal focus on the impact survivable, post-crash fire scenario. It will, however, also endeavor to address the applicability of improved protection techniques developed to counteract other fire scenarios recognizing that techniques offering a multiplicity of hazard control applications are inherently more attractive for future application. It is not the intent of this Lecture Series to suggest near-term modifications to airworthiness standards or regulatory requirements. The latter is left to appropriate authorities in various Nations in cooperation with the Aircraft Industry and Aircraft Users. Rather it is our purpose to review selected technical aspects, interject civil and military experience where possible, and provide a current look at the status of technological opportunities.

In addressing the survivable impact post crash fire situation, it is apparent that the ignition of aircraft fuel released during the crash is the primary cause of the majority of fires. Occasionally, particularly where petroleum based hydraulic fluids are present, mishaps associated with collapsed nose wheels and/or landing gear have triggered hydraulic fluid fires which subsequently have involved the interior cabin and/or the fuel system. The information available in mishap reports on aircraft accidents and incidents is generally lacking to establish with certainty the critical series of events in fire initiation, propagation and severity and their influence on passenger/crew survivability. A wide variance in the specific aspects of fire history is to be expected from one impact survivable mishap to another. In addressing the fire protection enhancement opportunities, consideration must be given to all the major elements capable of influencing the fire evolution process. Concurrently, attention must also be given to the heat, smoke, and toxic and irritant gases associated with the fire process and their effects on passenger egress and survivability. An integrated fire evolution/human survivability model inherently must be dynamic, is very complex, and difficult to develop. Consequently, one cannot in our present state of understanding divorce any of the major fuel/combustible elements when considering fire survivability enhancement opportunities.

Since the definition of the impact survivable, post crash fire scenario is still an "open" issue, we have endeavored to organize this Lecture Series to provide a discussion of some of the major elements involved from both the technologist and manufacturer viewpoints. Included is an up-to-date review of the aircraft mishap experience with particular focus on the impact survivable post crash fire mishap and the status of related fire modelling activities. This is complemented by an analysis of the psychological and physiological factors affecting human behavior and survivability. These two lectures will analyze the time related fire dynamics of the environment and the critical human response factors pertinent to survivability. As indicated earlier with respect to the fire threat, the on-board fuel has to be viewed as the biggest culprit. Those of us intimately associated with the aircraft fire safety area have long had the aspiration of an operational fuel which continues to provide the current standards of performance associated with conventional fuels but also possesses properties which would significantly minimize the in-flight and crash fire threats without economic or system safety penalties. The projected long-term energy crisis has triggered an intensive re-look at the availability of conventional aviation fuels and the impact of relaxing specification limits to accommodate products from poorer quality petroleum crudes and alternative sources such as tar sands, shale and coal. Consequently, we have included a lecture on the future aviation fuels outlook and how it might affect realization of the "safer" fuel aspiration. Several lectures will focus on selected aircraft sub-system fire protection engineering considerations. These will include fuel containment and fire and explosion suppression techniques, interior cabin materials development and simulated full-scale fire performance validation testing. We have also included a lecture on the aircraft manufacturer's approach to designing fire safety into modern flight vehicles and industry's assessment of the prospects for further improvement. Finally, we will address the opportunities for more effective ground fire fighting and rescue operations in the post-crash environment.

While a "dramatic" enhancement of aircraft fire safety, particularly in the crash environment, does not appear very likely as shown by prior in-depth analyses, gradual, positive improvements in safety can be expected. This Lecture Series will evidence some of the progress that is being made in our understanding of the fire phenomena involved, the factors influencing human survival, and various active and passive countermeasures and the validity of test methodology use for their assessment. Further, where safety enhancement, even in an incremental fashion, is clearly evident, continued positive responsivity of the aircraft industry to apply new technological improvements is to be anticipated.

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AIRCRAFT FIRE MISHAP EXPERIENCE/CRASH FIRE SCENARIO QUANTITATION

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SUMMARY

The results of a review presented in AGARD Advisory Report No. 132 of civil and military turbine aircraft accident and incident fire experience for the period 1964 - 1976 confirmed that the major post-crash fire hazard was caused by ignition of fuel released from wing separation failures during impact-survivable accidents. Other fire hazards in order of decreasing significance were caused by fuel released from major damage to fuel tanks, fuel tank explosions, fuel released from minor damage to fuel tanks and fuel lines, and the contribution of cabin materials in these fuel fire environments.

Generalized scenarios of these post-crash fire hazards are described and heat flux levels and cabin airflow rates based on full-scale and simulated fuselage post-crash fire tests are suggested for a fire scenario which occurred in an accident where the cabin with exit doors open was breached and partially enveloped in an external fuel fire. This paper also relates fire fatalities to the fire scenarios and updates the fire experience data base to include accidents through 1979 on the basis of recent transport aircraft crashworthiness studies conducted in the U.S.A. by the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee and the Boeing Commercial Airplane Company, Lockheed-California Company, and Douglas Aircraft Company under the sponsorship of the National Aeronautics and Space Administration and the Federal Aviation Administration. These studies concluded that the reduction of post-crash fires provides the greatest potential for improved crashworthiness and increased occupant survivability.

INTRODUCTION

Before the subject of aircraft post-crash fire experience is discussed, it is important to review the safety record of civil air carrier jet aircraft operations resulting from the continuing efforts of aircraft manufacturers, airlines, and government agencies to maintain safety as the primary consideration in air transportation. This concern is reflected in the decreasing accident rate for world-wide jet aircraft operations since the advent of jet transport trans-Atlantic service in 1958. The jet fleet accident rate for all types of accidents declined from over 60 accidents per million departures to about 2.5 per million departures at the end of 1979 (reference 1). In several countries, the fatal accident rate was less than 1.0 per million departures. In the United States, air carrier fatalities were less than 0.7 percent of all transportation fatalities in 1979 (reference 2). The U.S. air carriers flew a total of 280 billion passenger miles in 1979 and the fatality rate was 0.115 per hundred million passenger miles, compared to a fatality rate of about 1.6 in passenger car accidents (reference 3). It may be seen that the trend in jet transport travel over the years is for less fatalities as measured in terms of departures or passenger miles and that, compared with other modes of travel, travel by air carrier represents a significantly higher level of safety.

Aircraft accident experience has shown that this high level of safety enjoyed by the flying public may be increased if transport aircraft crashworthiness capability can be improved to enable more occupants to survive the crash impact forces and if the post-crash fire hazard can be reduced to enable the surviving occupants to evacuate the aircraft. It is obvious that efforts only to enhance occupant survivability by increasing the structural integrity of the fuselage would not be as beneficial if evacuation continues to be impeded by the post-crash fire threat. This paper concentrates on the post-crash fire threat and updates the post-crash fire experience and fire scenarios described in AGARD Advisory Report No. 132 on "Aircraft Fire Safety" in an attempt to provide guidelines for extrapolating laboratory fire test data to realistic situations and defining post-crash fire protection requirements.

DISCUSSION

Aircraft Accident Fire Experience

The AGARD Advisory Report No. 132 (reference 4) referred to a study by the Federal Aviation Administration (FAA) which indicated that there were 28 fatal impact-survivable U.S. turbine-powered transport accidents world-wide during 1964 - 1974 with a total of 987 fatalities (reference 5). It was estimated that 395 or 40 percent of the total fatalities were caused by fire or its effects in 23 of these accidents where post-crash fires occurred. Fourteen of the 23 fatal impact-survivable fire accidents involved fuel spillage following complete or partial wing separation failures which resulted in fuel fires and explosions that were primarily responsible for an estimated 259 fatalities or 26 percent of the total impact-survivable accident fatalities. Fuel tank explosions in two of the wing separation accidents contributed toward the cause of 75 fatalities by expanding and intensifying the post-crash fires so as to prevent further safe evacuation. The estimated 136 fire fatalities in the other nine post-crash fire accidents were probably caused by the combined effects of fuel fires, explosions, and interior material fires. Fuel tank explosions in two of these accidents contributed toward the cause of 51 fatalities.

The AGARD report also referred to a review by the Coordinating Research Council (CRC) of world-wide accident records between 1964 - 1974 which indicated that 97 impact-survivable accidents occurred to civil turbine transport aircraft during this period which resulted in post-crash fires (reference 6). Fuel was spilled as a result of complete or partial wing separation failures in 48 of these accidents (49 percent) and fuel tank explosions occurred in 11 accidents.

The fire experience data base may be expanded to include accidents in the period 1959 - 1979 on the basis of transport aircraft crashworthiness studies which were conducted by the Boeing Commercial Airplane Company, Lockheed-California Company, and Douglas Aircraft Company under the sponsorship of the National Aeronautics and Space Administration (NASA) and the FAA. Transport aircraft world-wide accident data were reviewed in these studies to define a range of crash conditions that may form the basis for developing improved crashworthiness design technology. The reports on these studies were published in April 1982 and contained certain recommendations which are being considered by the NASA and the FAA in planning a 10 year research and development program to improve the structural impact resistance of transport aircraft.

Boeing selected 153 impact-survivable accidents in their study from a total of 583 accidents of all types (reference 1). Post-crash fires occurred in 103 of the 153 accidents. In 95 of these cases, the aircraft was a hull loss and in the other 8 accidents, the aircraft suffered substantial damage. The accidents were assessed into the following 6 categories of accident severity:

1. Minor impact damage - includes engine/pylon damage or separation, minor lower fuselage damage, and minor fuel spillage.

2. Moderate impact damage gear separation or collapse - includes higher degrees of damage of type 1 and includes gear separation or collapse.

3. Severe impact damage - includes major fuel spillage due to wing lower surface tear and wing box damage, but no fuselage break.

4. Severe impact damage - includes severe lower fuselage crush and/or Class 1 or Class 2 fuselage breaks, may have gear collapse, but no tank rupture.

5. Extreme impact damage - includes Class 1 or Class 2 fuselage breaks with wing separation or breaks, may have gear and/or engine separation.

6. Aircraft destruction - includes Class 3 fuselage breaks or destruction with tank rupture, gear and/or engine separation.

Fuselage breaks: Class 1 - sections break but remain together
Class 2 - sections break and open
Class 3 - sections break and move off

Categories 1 through 3 involve accidents in which the occupant protective shell is generally maintained. Categories 4 through 6 refer to three classes of fuselage break to distinguish the severity of the accident. A Class 1 break has the fuselage broken with fuselage sections essentially remaining together. The opening allows fire entry but is too small for occupant egress. In Class 2 breaks, the fuselage separates sufficiently to allow occupant egress and fire entry, but the sections maintain a proximity to one another. Class 3 breaks have the fuselage sections separate and come to rest at some distance from each other. Category 4 accidents are severe accidents involving either severe lower fuselage crush or Class 1 and Class 2 fuselage breaks, or both, but there are no major fuel spills. Category 5 and 6 accidents involve increasingly severe destruction of the aircraft with major fuel spills.

The accidents in the Boeing study are summarized in Table 1:

TABLE I
Summary of Accidents

Cat.	Accidents	Hull Loss	Fire	Occupants	Total Fatalities No.	Total Fatalities %
1	5	3	4	616	53	8.6
2	24	12	6	1684	1	0.1
3	40	36	35	3425	875	25.5
4	22	20	9	2024	225	11.1
5	35	35	28	2618	934	35.7
6	20	20	18	1990	1547	77.7
UNK	7	7	3	311	156	50.2
	153	133	103	12668	3791	29.9

The fatalities are summarized in Table II:

Table II
Causes of Fatalities
(% of total fatalities)

	Fire		Trauma		Other		Unknown	
Cat.	No.	%	No.	%	No.	%	No.	%
1	53	100.0	0	0	0	0	0	0
2	0	0	1	100.0	0	0	0	0
3	722	82.5	5	0.6	18	2.1	130	14.9
4	55	24.4	5	2.2	165	73.3	0	0
5	335	35.9	210	22.5	32	3.4	357	38.2
6	189	12.2	190	12.3	3	0.2	1165	75.3
UNK	2	1.3	65	41.7	0	0	89	57.1
	1356	35.8	476	12.6	218	5.8	1741	45.9

It may be observed from these data that fire presents the greatest hazard regarding overall survivability since the known fire fatalities represent 35.8 percent of the total fatalities and outnumber the known trauma fatalities by a factor of 2.84:1.0. The fire hazard is most severe for accident categories 3, 5, and 6 having major fuel spills. Category 3 accidents involved 722 fire related fatalities which included 108 fatalities in an accident at Toronto that were treated as fire related because the aircraft exploded while attempting a go-around after a major fuel spill occurred from tank damage following a hard landing. Category 5 accidents resulted in 335 fatalities which were known as fire related. The Tenerife accident accounted for 36 percent of the fatalities, with 144 fatalities of undetermined cause. Of the known causes of fatalities in the category 6 accidents, 189 were related to fire and 190 to trauma.

Fuel spillage occurred in 134 of the 153 impact-survivable accidents selected in the Boeing study and post-crash fires of varying severity resulting from fuel spillage were experienced in 98 accidents. Fuel spillage caused by wing separation failures occurred in 77 accidents with 62 post-crash fires. Wing separation failures due to impacting trees and similar obstructions frequently occur at the root-inboard section (reference 2) and are particularly severe in regard to size of the fuel spill and resulting fire and incidence of fire related fatalities. In 21 such accidents, large spills occurred in at least 16 with fires occurring in at least 15. No fire related fatalities occurred in only 7 accidents. Fire entry through fuselage breaks occurred in almost 60 percent of the 62 accidents while entry by burn-through occurred in about 10 percent. Fire was a factor in evacuation in about 30 percent of the accidents. It may be observed from these data that wing separation failures result in a high percentage of fires and fire related fatalities and a high probability that fire will enter the fuselage either through a fuselage opening or by a burn-through.

Fuel spillage caused by fuel tank rupture due to to lower surface tear occurred in 27 accidents with 24 fires. Fire was a cause of fatalities in 11 of the post-crash fire accidents. These fuel tank lower surface tear failures resulted in large fuel spillage and severe fires. In about 60 percent of the fuel spills, fire entered the fuselage by burn-through while fire entry through fuselage breaks occurred in 15 percent and by other routes in about 10 percent. Fire affected evacuation in 40 percent of the accidents.

Fuel spillage caused by fuel tank rupture/wing box tear due to separation of wing-mounted landing gear or engine pods probably occurred in 24 accidents. Landing gear tear is known to have occurred in 5 and probably occurred in 10 other accidents. All 15 fuel spill accidents resulted in fire with 60 percent of the accidents having fire related fatalities. Fuel spills were large and only one fire was considered small. Fire entry to the fuselage was by fuselage breaks in 6 accidents and burn-through in 2 accidents. Fire had an effect on evacuation in 80 percent of the accidents. Engine pylon tear of the wing box occurred in 2 and probably occurred in 7 other accidents. Fire resulted in all 9 accidents with fire related fatalities in 4 accidents. Fuel spillage from more than one type of tank damage was considered to have occurred in 12 of the probable landing gear or pylon tear accidents.

Fuel spillage caused by puncture of fuel tanks by foreign objects occurred in 3 accidents and resulted in fires in 2 of the accidents that destroyed the aircraft but there were no fatalities. Fuel spillage from leaking tanks occurred in 4 accidents and resulted in fire in one accident that destroyed the aircraft but there were also no fatalities.

Fuel spillage caused by rupture of fuselage fuel lines in aircraft having aft-fuselage mounted engines is known to have occurred in 6 and probably occurred in 4 other accidents. All 10 accidents resulted in fires with fire related fatalities in 9 accidents. Fuel line rupture fires had an effect on evacuation in possibly 6 accidents. Fuselage breaks were present in 8 accidents with fire entering the fuselage through the breaks in 6 accidents. Fire entered through the floor in 3 accidents and possibly in another.

There were 2 accidents in which vapors or fuel spillage through fuel tank vent lines were major contributors to fires. In one accident, an external fire entered the vent outlet with resulting fuel tank explosions. In the other accident, fuel spillage occurred from a fuel tank through the vent line due to the tilt of the aircraft. In this case, the flow of fuel could not be stopped and fire eventually destroyed the aircraft.

Fuel tank explosions occurred in 20 accidents including 6 probable cases with fire related fatalities in 15 accidents and possibly 3 others. The explosions had an effect on evacuation in 80 percent of the accidents.

Fuel was not involved in 4 accidents where fires resulted from ignition by friction. Three accidents involved nose landing gear collapse or separation which allowed the lower fuselage to contact the runway.

The fires in 2 accidents resulted in hull loss and were minor in the other two. There were no fire related fatalities in these friction fire accidents.

As previously stated, the accident experience shows that fire presents the greatest hazard regarding overall survivability in impact-survivable accidents and, as might be anticipated, the post-crash fire hazard increases as the severity of the accident increases. When the various fire threats encompassing the overall post-crash fire hazard are assessed in view of the likelihood of survival and the number of occurrences in actual aircraft fire experience, the individual fire hazards may be ranked in the following order of decreasing severity and described in generalized post-crash fire scenarios:

Post-Crash Fire Hazard Severity Ranking

1. Major fuel spill fires due to wing/partial wing separation - Extreme impact damage (Category 5)
2. Major fuel spill fires due to fuel tank rupture/wing lower surface tear and wing box damage - Severe impact damage (Category 3)
3. Major fuel spill fires due to tank rupture - Aircraft destruction (Category 6)
4. Fuel tank explosions (Category 1 et al.)
5. Fuel spill fires due to rupture of fuselage fuel lines (Category 4)
6. Non-fuel spill fires due to ignition by friction.

Generalized Aircraft Post-Crash Fire Scenarios

1. Post-Crash Fires Due to Wing Separation (Category 5 Accidents) and Fuel Tank Explosions (Category 1 et al.)

Accidents have occurred where aircraft either undershot on approach or failed to become or remain airborne during takeoff and collided with structures, trees, drainage ditches and other obstacles, resulting in wing separation and release of large quantities of fuel. The fire characteristics pertinent to this fire threat scenario are based on fuel release inflight following collision with obstacles prior to impact with the ground and/or during ground deceleration due to (1) initial fuel system structural damage of one wing followed by separation of the other wing and (2) separation of both wings or parts of both wings. The air shear forces imparted to fuel released in the dynamic phase of a survivable accident causes the formation of a fine mist of small droplets which is readily ignited, resulting in a fire which can envelop the aircraft and serve as an ignition source for continuing fuel spillage as the aircraft comes to rest. It is estimated that the duration of the dynamic phase may be up to 10 seconds, i.e., the period while the aircraft is in motion from the moment of initial damage resulting in fuel spillage until the aircraft comes to rest. Ignition sources during this period will include hot engine surfaces, internal engine fire due to fuel ingestion, severed electrical wiring, friction sparks, hot brakes, and other sources which appear as progressive damage is inflicted. The fire developed during the dynamic phase serves as the ignition source for fuel spilled while the aircraft is at rest and for explosions in undamaged fuel tanks.

The fire threat scenario resulting from the ignition of large quantities of fuel released under dynamic conditions may consist of several threats of steadily increasing intensity and severity. Fire broke out on the left side of the aircraft in a takeoff accident where initial structural damage was incurred in the left wing area, followed by a large fire which erupted on the right side of the aircraft after the right wing was torn loose, spilling the fuel contained therein. Several minutes after the accident occurred, two fairly large explosions occurred at the left side of the aircraft. Subsequent explosions occurred and hampered fire-fighting and rescue operations. An explosion also took place in another takeoff accident following wing separation as the aircraft struck railroad tracks. In approach undershoot accidents, fires have been initiated inflight following impact with structures and while passing through trees upon fuel spillage from severely damaged and separated wing tanks. These external fires move along with the aircraft as the aircraft come to rest and develop into intense ground fires which destroy the aircraft. A series of explosions occurred shortly after the aircraft involved in the approach inflight fire accident came to rest, expanding the fire so that further evacuation was impossible.

Fuel tank explosions which have occurred during impact-survivable accidents have been caused by external fires fed by fuel released from severed wings, damaged tanks, or damaged fuel lines. These external fires create high fuel tank surface temperatures resulting in autogenous ignition or ignite the vapors in the vent outlet resulting in flames which propagate through the vent system into the fuel tanks. The explosions may expand the external fires and hamper fire-fighting and rescue operations in addition to creating non-survivable conditions which impede evacuation. In one accident where the aircraft took off following a hard touchdown during which an engine and pylon separated from the aircraft along with a piece of the bottom surface of a fuel tank, an explosion occurred in that fuel tank about 2 1/2 minutes after touch down, followed 6 seconds later by an explosion in an inboard tank, and then by a third explosion which caused the loss of a large section of the wing. The combination of escaping fuel and the shorting of electrical circuits in a severed electrical harness may have been the primary cause for the first explosion which then caused the subsequent explosions.

Fuel tank explosions have occurred while the aircraft were parked and were being fueled or in connection with maintenance work being performed on the fuel system. The refueling explosions have been caused by ignition of fuel vapor due to a static discharge of an electrostatic field above the fuel. The maintenance explosions were the result of electrical arcs in fuel system components or fuel tank purging operations where the blower used for purging the tank created a flame front which propagated into the tank. Fuel volatility has a major effect in these explosions since explosions with low volatility kerosene type fuels have usually resulted in minor to moderate aircraft damage while explosions with high volatility wide-cut fuels have usually resulted in major damage or total destruction (reference 6).

2. Post-Crash Fires Due to Tank or Fuel Line Rupture (Category 3, 4, and 6 Accidents)

Fuel tank or fuel line damage has occurred in accidents which have occurred during the takeoff roll and landing run as a result of landing gear failure or impact with obstacles due to insufficient directional control and during approach and takeoff climb following contact with structure, trees, high ground, or other obstacles.

The possible effects of local damage to fuel tanks or fuel lines during impact-survivable accidents range from release of no fuel as some tanks may be empty to release of large amounts of fuel leading to fires approaching the severity described in the wing separation fire scenario. Fuel has also been released from damaged tanks without resulting in fire in non-fatal accidents. If the spilled fuel is ignited, the probable ignition sources are comparable to those in the wing separation scenario and will include hot engine surfaces, engine fuel ingestion, severed electrical wiring, friction sparks or hot brakes.

The fire characteristics pertinent to this fire threat scenario range from small fires fed by fuel released from slightly damaged tanks which are relatively easy to control to severe fires following massive tank damage which can eventually destroy the aircraft. Similar degrees of fire severity may be produced following damage to fuel lines caused by engine dislocation, engine failure, or landing gear failure as a function of elapsed time prior to shutoff valve actuation. The deceleration/impact forces in accidents resulting in fuel tank/line damage are usually less than in wing separation accidents so that the number of impact fatalities is less and the percentage of fire fatalities is higher.

3. Post-Crash Non-Fuel Spill Fires Due to Friction Ignition

A collapsed landing gear ground fire scenario was initiated when an aircraft made a firm landing on the nose gear first which caused the nose gear and wheel well structure to be pushed aft and upward into the fuselage. Fire erupted in the lower electronic bay area beneath the floor of the flight deck which was fed by hydraulic fluid from two fractured nose wheel steering hydraulic lines. The fire was not contained and eventually destroyed the interior of the cockpit and passenger cabin. Another landing gear ground fire scenario was caused by tire failure during the takeoff run which prompted the crew to reject the takeoff. Pieces of burst tires and/or wheel rims had damaged the hydraulic lines on the landing gear strut and the elevated brake temperature or wheel friction sparks ignited the released hydraulic fluid. When the airplane came to rest, there was a small fire at the front tires of the landing gear. The hydraulic fluid spread and the fire enlarged such that smoke penetrated into the cabin 6 minutes after the airplane had stopped. After another 6 minutes, the fire had caused the fuselage to fail and the tail section touched the runway. The fire continued to burn for more than 8 hours and almost totally consumed the airplane.

A Scenario of the Contribution of Interior Materials to the Post-Crash Fire Hazard

Major post-crash external fuel fires can burn through the fuselage skin or floor in 40 to 60 seconds or can enter through a fuselage break or other opening and may be generally fatal before the interior materials generate lethal quantities of smoke and toxic gases, but ignited materials have produced significant amounts of smoke and toxic gases in several accidents to impede evacuation and cause fatalities.

An AGARD analysis by Snyder (reference 7) of NATO member air transport accidents, 1964-1975, revealed that injuries and fatalities were primarily due to the post-crash effects of fire, smoke and toxic fumes, and secondarily to crash impact. It was noted in this analysis that toxic gas emission from burning cabin materials has only recently had serious attention as a result of findings in several major accidents occurring within the past decade. Nine air carrier accidents were identified as being of particular note in this regard where the majority of the 356 fatalities have been attributed to the toxic effects of smoke and fumes or the thermal effects of fire. It was pointed out that in 3 of these accidents, 105 of 261 passengers aboard died in attempts to escape during the one to three minutes prior to the buildup of lethal thermotoxic environment within the cabin. In 4 of the other accidents, significant amounts of hydrogen cyanide were found in victim blood levels which attests to the fact that aircraft materials contributed to the lethality of the smoke in some post-crash aircraft fires, since burning fuel alone would not produce cyanide.

The entry of external fuel fire into the cabin was apparently the predominant hazard in the accidents where fatalities occurred prior to the buildup of a lethal toxic gas environment. Studies of fuel pool fires have shown that a fully developed fire can produce a radiant heat flux of about 14 British Thermal Units per square foot per second (Btu/ft^2 sec) and a fire scenario has been developed to investigate the effects of burning interior materials when ignited by this intense radiant heat such as probably occurred in the other accidents. Full-scale fuselage post-crash fire tests are being conducted using an intact simulated wide-body passenger cabin with a door-size opening adjacent to a large external fuel fire (reference 8). Initial tests were conducted with no interior materials in the cabin to determine the hazards of the external fuel fire alone when it entered through the door and indicated that the heat flux level of 14 Btu/ft^2 sec at the door rapidly dropped to less than 2 Btu/ft^2 sec at a distance of about 10 feet from the door. While hazardous temperatures and dense black smoke were developed, insignificant concentrations of carbon monoxide and a minimal depletion of oxygen were measured. Tests with seats and interior furnishings subsequently installed in the cabin which were ignited by the fuel fire have, therefore, been able to identify the hazards which are created solely by the burning materials.

Based on a number of simulated and full-scale fire tests which were conducted in accordance with this scenario, heat flux values of 2.2, 3.08, and 4.41 Btu/ft^2 sec (2.5, 3.5, and 5.0 W/cm^2) were selected as being within the heat flux range probably existing in a survivable cabin environment for use in an experimental program to develop a procedure for testing and ranking interior materials for their total combustion hazards (reference 9). An air flow rate of 875 ft^3/min was considered to be representative of the air flow through open doors in the cabin following a survivable accident. It was the objective of this program to develop a laboratory scale ranking method called the "Combined Hazard Index" (CHI) which is expressed as the number of seconds of a crash fire scenario burn time available for passengers to escape from a cabin in which an interior material in involved in fire. In this approach, occupant escape time becomes the common denominator relating the thermotoxic environment accumulating in the cabin to occupant incapacitation. However, it should be kept in mind that the influence of burning materials on survivability and evacuation is also interrelated with the extent of structural damage, impact injuries, discipline and order among the crewmembers and passengers, and whether the accident occurred at night or in daylight.

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HUMAN RESPONSE TO FIRE

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SUMMARY

This lecture series addresses human survival in aircraft fires. The discussion begins with a review of aircraft fires and human survival in terms of the thermal-physical dimensions and properties of aircraft fires, the chemical and toxic nature of fires, the concept of a worst-credible environment, and the dimensions of survival time as derived from a consideration of ground and airborne fire suppression and an aircraft fire analog in the form of a racing accident.

Having defined the threat, the discussion continues with a review of the epidemiology of human fire morbidity and mortality. In this section we consider human morbidity and mortality under three sets of circumstances: (1) no personal protection - no prevention of fire; (2) inadequate protection - no prevention of fire; and (3) prevention of fire and good protection. Following the epidemiology discussion, we critically examine the theoretical and practical aspects of survival through prevention and protection. Reduction of fire induced death and elimination of fire related injuries in otherwise survivable aircraft accidents are possible and have been demonstrated in large fleets of aircraft. Prevention of the fire alone or in combination with protective garments will yield the desired results. We discuss in some detail the helicopter crashworthy fuel system and its cost relationship to burn injury cost prevention. All the concepts of personal protection through the use of fire protective garments are discussed with attention given to the biomedical trade-offs. Uniform comfort, degree of protection, and cost are also compared. The introduction of protective fabrics leads to a discussion of the assessment techniques used to select fabrics best suited for protective clothing.

Four different assessment techniques will be covered: (1) fire pit testing of ensembles; (2) laboratory flammability and thermal transfer measurements on fabric samples; (3) bioassay tests on samples using animals as human analogs; and (4) predictive modeling.

The lecture will close with a review of current technology covering: (1) use of underwear as insulating layers in ensembles; (2) capabilities of various fabrics; (3) developments in crashworthy engineering; (4) foam filled suits; and (5) fire suppressants such as Halon.

This lecture will build a physical and biomedical basis upon which to formulate strategies for the development of aircraft fire prevention and personal protection leading to increased human survival.

INTRODUCTION

Human burns are emotionally and visually hideous. The treatment of burns imposes a heavy medical logistic load. Convalescence is long, and treatment is expensive. The patient's return to a normal life, if he has been severely burned, is not certain. Returning to pre-injury occupation may be impossible. Aviators and other aircrewmen rarely return to flying after survivable burns in a postcrash fire. What is even more unfortunate is that most do not survive.

The postcrash fire is an ever-present threat in aircraft crashes, especially those involving helicopters. While impact forces are the primary cause of injury and death, fire takes a disproportionate toll of life in those accidents that would be otherwise survivable. The fires occur immediately, involve the crew compartment, and are very severe. The prevention of burn injury and death is a tremendous engineering and medical challenge. Preventing the fire can be accomplished through new structural design, crash resistant fuel systems, and new fuels. This technology is being applied with excellent results, but it will be a long time before the application is widespread, and then only a few aircraft will benefit from this protection. Therefore, the aviator must be surrounded with a protective microenvironment that will provide a few precious seconds of protection as he extricates himself from the aircraft and runs through the fireball. This microenvironment is created by a protective helmet, visor, gloves, boots, and a flight suit constructed of some thermal protective or resistive material. The selection of the best techniques and materials to meet all design requirements and provide the maximum thermal protection is difficult. Until recently, the decision criteria were based on laboratory data derived from physical thermal sensors like thermocouples, skin simulants, and heat sensitive chemicals. From a textile viewpoint, these data provide an excellent engineering base; however, they are not reliable for making medical decisions regarding which material is most effective in preventing burns regardless of what happens to the fabric.

Twelve years ago the authors were asked to develop biologically valid methods of assessing the various techniques used in improving human survivability from a postcrash fire. These included an epidemiologic analysis of fire injuries; an analysis of fire rescue and fire fighting techniques as they apply to rotary-wing and light to medium fixed-wing aircraft; and the evaluation of various protective garments, fabrics, and ensembles. After the aircraft fire problem had been defined, a rather extensive program evolved that began with a description of a worst-credible postcrash fire complete in its physical, thermochemical, and environmental aspects. Large series of aircraft postcrash fire mishaps were analyzed and the survivors interviewed. Assistance was given to the engineering community as it worked to design fuel systems that were resistant to crash and would prevent the fire from occurring. The best and most likely avenues for successfully improving survivability were identified. A method was devised to bring the characteristics of a typical postcrash fire into the laboratory so that routine experimentation could be performed. What followed was a series of experiments to define the engineering mechanics of fire induced burns. These data were used to correlate and validate the physical thermal sensors used by the textile engineering community against living tissue when both sensor and skin are exposed to an identical thermal threat. These data were in turn used to evaluate various protective fabric ensembles under development and in current use. Lastly, mathematical models have been designed to predict burn survivability.

In order to determine the effectiveness of the various techniques used to reduce the fire hazard and improve human survivability, a comprehensive epidemiologic study was conducted comparing fire related morbidity and mortality to aircraft mishaps with and without optimum protection.

This lecture will highlight some of the features of this program and serve to demonstrate that human beings can indeed survive aircraft accidents without significant thermal injury where postcrash fire is an ever-present threat.

POSTCRASH FIRE ENVIRONMENT

The postcrash fire environment as it relates to human survival has been extensively studied in numerous test programs. There has been extensive analysis throughout the international community of aircraft accidents involving fire related deaths. There are many similarities between the postcrash fires found associated with automobile racing and those seen in the general aviation community, especially involving light fixed-wing and rotary-wing aircraft. From these many studies, the most significant factors influencing survivability in postcrash fires have emerged.

Many variables can influence the magnitude and threat of a postcrash fire. These include the relative wind, type of terrain into which the flammable fluid has drained, the fuel distribution, degree of structural damage, location of the fuel spillage within the aircraft, vaporization, number of structural openings, degree of spill, and type of fuel used. However, the factors that best describe the postcrash fire situation from terms of possible human survival are smoke, toxic gases, heat, and, most importantly, the associated time relationships.

Smoke

Postcrash fire generates large quantities of dense smoke consisting of unburned carbon particles, ashes, and gaseous combustion products. These come from three basic fire sources. The first and most important is the burning of the fuel itself. The amount of smoke related to the fuel is dependent upon the type of fuel. Alcohols contribute essentially no smoke, with the long chain carbon rich diesel molecules contributing much sooty smoke. The ratio of fuel to air will also determine the amount of smoke. Trapped fuel burning in closed compartments and spaces where the amount of available oxygen is rapidly decreased, such as wing compartments, cargo hulls, or in dense foliage, worsen the smoke.

The second common source of smoke in all types of fires, but especially bad in large cargo and air transport aircraft, is from the ignition of the polymeric materials used in interior design structures. These include the synthetic fabrics of seats, carpets, drapes, lap robes, and sound deadening insulation. Also of concern are the polymeric based plastics used in interior walls, bulk heads, and ancillary equipment such as counter tops, serving trays, and other structures. The increasing use of composite materials with their superior strength-to-weight ratio and resistance to fatigue crack propagation has structural advantages over most traditional metallic alloys. Most of these composites are bound with polymeric resins which burn even though the matrix such as Fiberglas or boron graphite will not.

The third souce of smoke comes from the secondary ignition of fabrics, materials, and structures made from vegetable or organic fibers such as paper, fiber board, cotton, wool, and wood. This smoke is of little concern.

The rapid obscuration of vision by smoke, especially in large air transport aircraft, has been repeatedly reported by survivors of aircraft postcrash fires. Many have stated they were unable to see the emergency lighting systems at the exits. This has led human factors and lighting engineers to make strong recommendations over the years for high intensity, crash resistant interior lighting and exit identification systems. Smoke obscuration causes confusion and panic and is thought to be one of the critical factors in delaying or preventing the escape process in otherwise survivable fires.

Toxic Gases

Death associated with fire is often attributed to smoke inhalation. It is common to hear of fire fighter injuries that are related to smoke inhalation. In fact, the inhalation of soot or carbon particles by themselves, unless they are hot enough to do damage to the respiratory tract or cause uncontrolled coughing reflexes, are of minimal physiologic or survival concern. Unfortunately, where there is smoke, there are almost certainly toxic gases. The predominant toxic byproduct of the combustion of fuel, especially where fuel air mixtures are reduced as described in the discussion on smoke, is carbon monoxide. Carbon monoxide has an unusual affinity for the hemoglobin pigments found in human red cells which normally function to carry oxygen to the body's cells. The formation of carboxyhemoglobin effectively blocks oxygen pick up and release by the hemoglobin molecule. If the concentrations of atmospheric carbon monoxide are high enough, incapacitation and even death can be extremely rapid. But, as shown in Figures 1 and 2, lethal concentrations of carbon monoxide do not occur immediately. By that time other factors will have taken on much greater importance; primarily, heat itself.

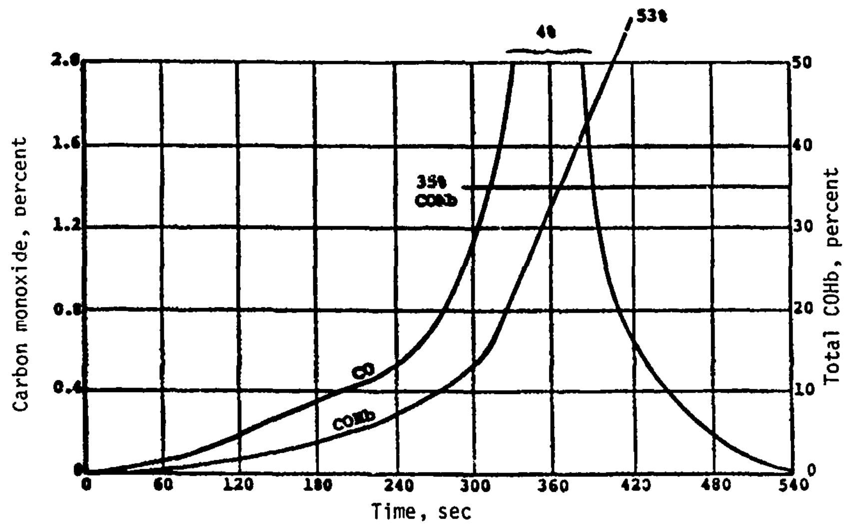


FIGURE 1. Average Recorded CO Concentrations and Calculated COHb Levels in Large, Crashed, Burning, Passenger/Cargo-Carrying Fixed-Wing Aircraft.

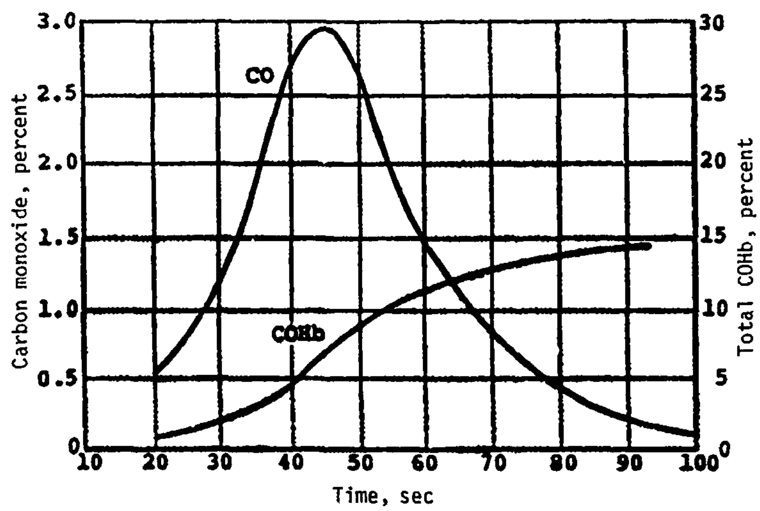


FIGURE 2. Average Recorded CO Concentrations and Calculated COHb Levels in Large, Crashed, Burning, Passenger/Cargo-Carrying Helicopters.

Perhaps of greater concern is the toxicity from the pyrolytic byproducts of the polymeric materials found in aircraft. Table I summarizes some of the more significant toxic byproducts. Some byproducts like phosgene can be incapacitating at very low concentrations and with few breaths. Respiratory protection can play a role in survival. Respiratory protection is an essential component of the fire fighter's gear, especially those involved in mine accidents, large building fires, and oil field fires. Many jet pilots owe their lives to their training and disciplined use of their oxygen mask in a smoke and toxic gas filled cockpit. Considerable experimentation and several significant recommendations have been made to provide disposable smoke hoods for occupants of large bodied air transport aircraft and building and ship occupants that could be used in the event of a fire.

TABLE I
TYPICAL TOXIC PRODUCTS OF INCOMPLETE COMBUSTION OF VARIOUS MATERIALS
(in addition to carbon monoxide)

Material	Product
Cellulose acetate, some vinyl plastics	Acetic acid
Nitrogen--containing plastics, such as the urea-, melamine-, and aniline-formaldehydes	Hydrogen cyanide (HCN), ammonia
Phenol-formaldehyde plastics	Phenol-formaldehyde (HCHO)
Chlorine--containing plastics, such as vinyl chloride and vinylidene chloride	Hydrochloric acid (HCl), carbonyl chloride (phosgene, COCl)
Alkyd resins, and others based on, or derived from glycerine	Acrolein
Wood	Formaldehyde, acetic acid
Wool, silk, leather, cheese	Hydrogen cyanide
Butter and fat	Acrolein

Heat and Fire

The chemical and physical processes that determine the formation of a fire plume above a volatile pool of hydrocarbon aircraft fuel are characterized by the coupling of complex hydrodynamic, thermodynamic, chemical heat, and mass transfer mechanisms together with the geometry and extent of the fuel source, air supply, and instantaneous atmospheric conditions. The thermochemical and physical descriptions of a postcrash fire have a relationship to human survival only in how they translate to heat on the skin and in the respiratory tract and, more importantly, thermal flux or heat applied to a dimension of space or surface for a defined period of time expressed as calories (C) per square centimeter (cm^2) per unit of time (seconds). Actual temperatures experienced within a postcrash fire can vary widely in onset rate and peak values reached. Large bodied aircraft may experience considerable interior atmospheric heating long before aircraft skin burn-through occurs. Fuselages with large openings made either by the crash or in the form of windows and doors usually heat up rapidly. Fabric covered aircraft and helicopters heat up at almost the same rate as a free field fire. Figures 3 and 4 describe typical interior temperatures in large bodied and small bodied aircraft surrounded by fire.

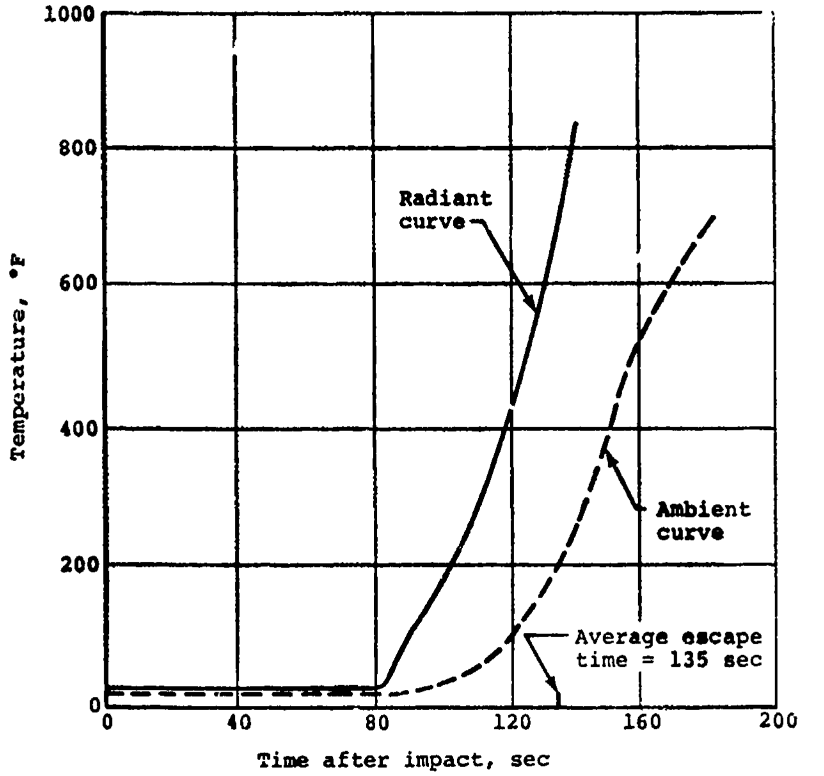


FIGURE 3. Average Recorded Ambient and Radiant Temperatures in Large, Crashed, Burning, Passenger/Cargo-Carrying, Fixed-Wing Aircraft.

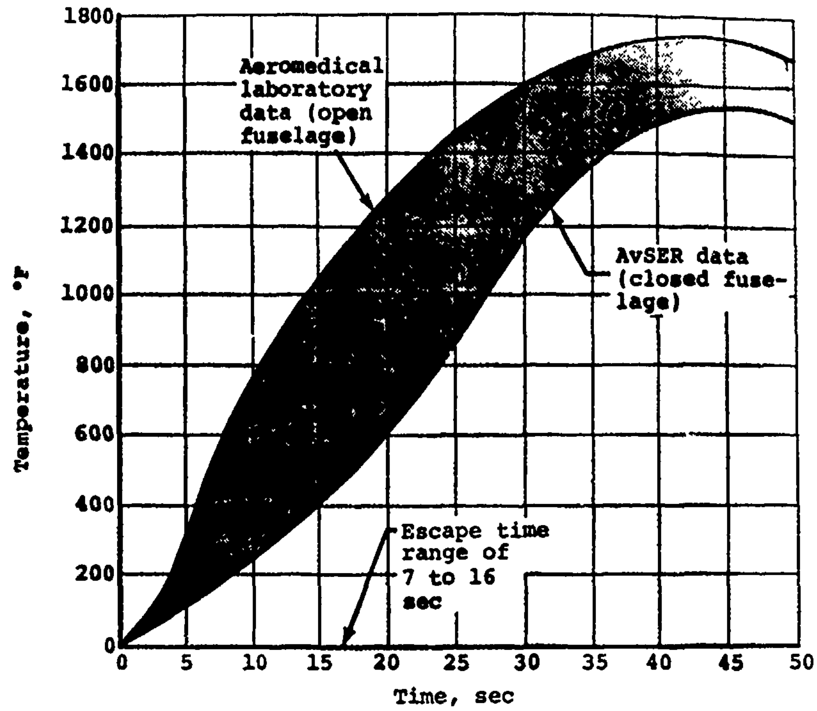


FIGURE 4. Recorded Ambient Temperature Range in the Cabin Areas of Large, Burning, Passenger/Cargo-Carrying Helicopters.

The fire itself is one gigantic petrochemical cracking tower that is self sustaining as the molecular structure of the fuel and exposed structures are heated, decomposed, and ignited. There has been some concern that survival from chemically dirty fuel fires might be worse than those from relatively clean fuels. Our research has shown that there is little significant chemical interaction with the body. Long chain hydrocarbon fuel fires that are particularly sooty have very high radiant energy components from the luminescence of the particulate materials (primarily carbon). The cataclysmic physical properties of a fire create conduction and convection thermal transport phenomena that are of primary concern to survival only if they bring the heat source to the individual or, in the cases of certain atmospheric conditions, move the heat in the fire plume away from the survivor. As we will discuss in a moment, this latter phenomenon will allow one occupant to emerge from a fireball essentially unscathed while another is consumed.

Keeping these considerations in mind, within a free field fire or one that can be considered thermodynamically to be infinitely deep, it is the radiation of heat that plays the principal role in survival from a postcrash fire. Figure 5, from the work of Pryer and Yuill, depicts predicted human tolerance to acute exposure to ambient air temperatures where the predominant heat transfer mechanism is via the conductivity existing between air molecules and skin. Figure 6 depicts typical skin pain thresholds as a function of the temperature of a predominantly radiant heat source. When exposed to high temperatures there are two factors to be considered in determining a person's survivability. They are tolerance to pain, which signals injury and tissue damage, and the thermal level at which exposed skin will experience at least second-degree burning. When human skin is heated suddenly to temperatures between 108 degrees Fahrenheit and 113 degrees Fahrenheit, pain is experienced. This usually becomes unbearable at about 124 degrees Fahrenheit. The rate of heat rise and exothermic intensity of the thermal source influence damage and, thus, survivability. During exposure to a postcrash fire, the heat flux is so intense and so constant as to do irreparable damage very early in the exposure. Human beings have been known to survive very high environmental heat loads where exposure has been gradual; thus, allowing the body's adaptive physiologic systems, such as peripheral dilation of capillary beds, the sweating mechanism, and other cardiovascular dynamics, to come into play to cool the body. None of these factors play a significant role in survival from acute heat exposures of a fire.

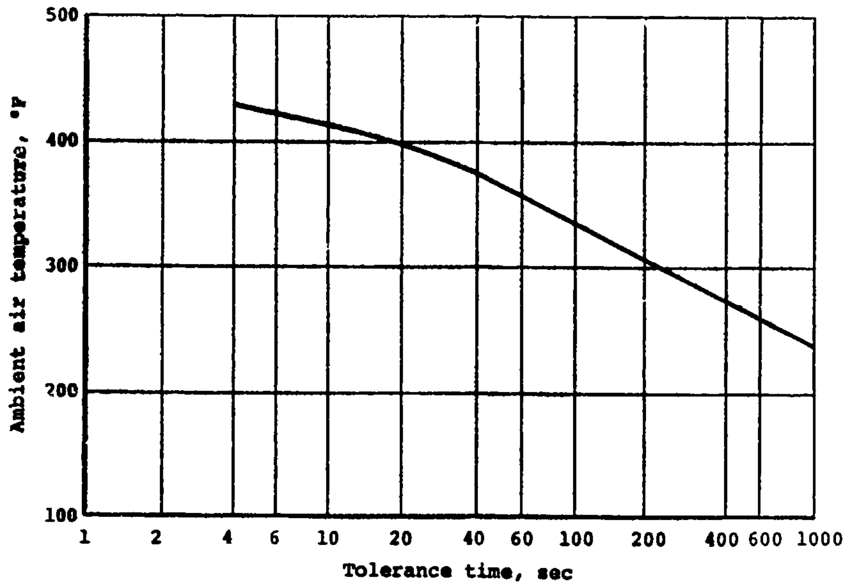


FIGURE 5. Human Tolerance to Ambient Air Temperatures.

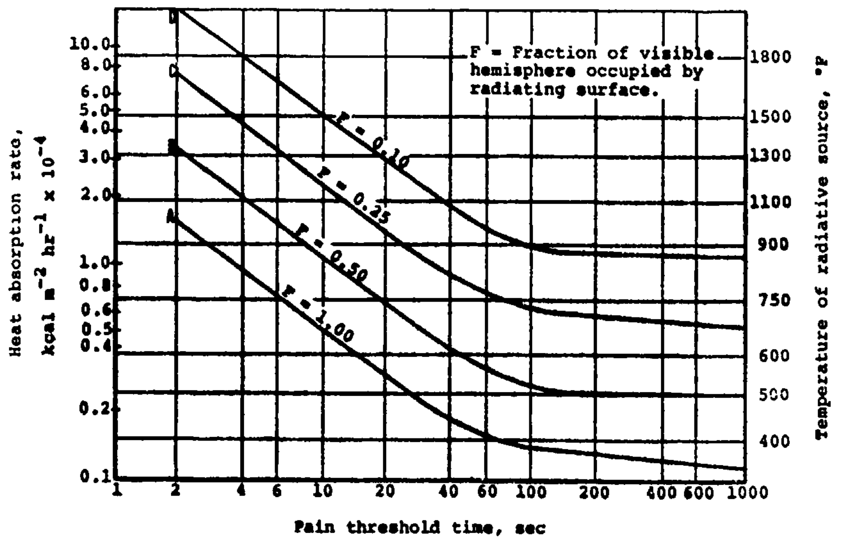


FIGURE 6. Pain Threshold Time as a Function of Temperature of Radiant Heat Source.

Worst-Credible Environment (WCE)

As it relates to a postcrash fire, the definition of WCE means an explicit statement of the worst conditions in a postcrash fire that can be experienced with a reasonable chance of survival, provided certain protective techniques are used. For very practical reasons, the rest of this lecture will concentrate only on the heat aspects of a postcrash fire.

A typical ambient and radiant temperature curve for large cargo passenger carrying aircraft is shown in Figure 3. As can be seen, little temperature increase occurs until approximately 80 seconds after impact. One of the main reasons for the delay in temperature rise is the protective shield afforded by the fuselage as seen in Figure 7. Fuselage skin burn-through averaged about 80 seconds, although the range of burn-through times varied between 40 seconds to over 120 seconds. Calculated escape times based on human tolerance to heat varied from 53 to 220 seconds, with the average escape time equal to 140 seconds. It is during these long available escape times that smoke and toxic gases are of significance. Breath holding, which can be livesaving in a fire, becomes almost impossible when a person is panic stricken, prone to hyperventilation, or exercising violently during the escape process.

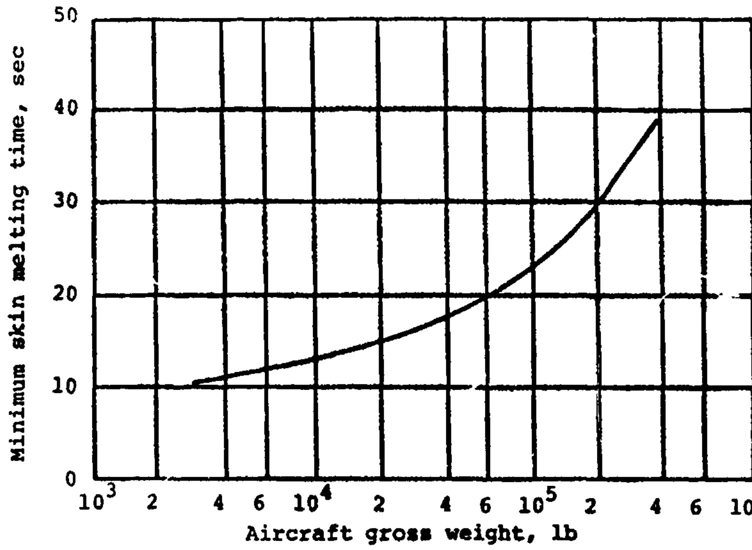


FIGURE 7. Aircraft Skin Melting Time Based on Gross Weight.

An ambient temperature range typical for light utility and passenger carrying light to medium fixed-wing and rotary-wing aircraft is presented in Figure 4. This figure shows that the temperature started to rise almost immediately after the crash. The early temperature rise was due to two factors. One was that extensive structural breakup occurred upon impact causing openings that allowed air to be drawn in providing oxygen for internal combustion processes. The second factor was that most of these aircraft had fuselage habitable space and fuel located in close proximity to one another. In other words, the fire and occupiable space were geometrically almost one and the same. We see that the average maximum time to escape ranges from seven seconds for helicopter and open-fuselage aircraft to 16 seconds for closed-fuselage aircraft in this size category. Smoke, carbon monoxide, and toxic fumes are of little concern in these rapidly developing fires. Breath holding becomes an important lifesaving technique. Though light fixed-wing and helicopter postcrash fires can be immediately intense, the quantity of fuel spilled ranges from as little as 10-15 gallons to rarely more than 200 gallons thus, limiting the size of the fireball. The provision of a thermal protective suit offering three or four seconds of protection against second-degree burns and perhaps a second or two more against third-degree burns now takes on gigantic relative importance in extending these escape times.

After conducting a large series of actual aircraft fires, open field fuel fires, and instrumenting human surrogates within these fires, we define the worst-credible environment as an infinitely deep, luminescent fire with a surface temperature of 1800-2100 degrees Fahrenheit, with 60-80 percent of its heat transmitted to the skin in the form of radiant energy at a thermal flux of 3.5-4 calories per centimeter squared per second. This roughly equates to a six-second radiant exposure of skin to a radiant wall of heat at 2100 degrees giving a surface skin temperature at the end of the exposure of 400 degrees Fahrenheit.

POSTCRASH FIRE RESCUE

All modern airports and most military airfields are equipped with technologically advanced and very expensive fire fighting equipment manned by highly trained teams. Large transport or cargo aircraft experiencing takeoff or landing accidents in which there is a postcrash fire with the associated prolonged maximum survival times can benefit from rapid reaction fire fighting methods. However, when the accident occurs off the improved airfield outside the boundary fence or in a farmer's field or a city business or residential area, this sophisticated fire fighting gear is of essentially no value in improving human survival. The use of foamed runways and equipment standing by to rapidly extinguish onboard fires, when an aircraft lands with a declared emergency, can be helpful in improving survival.

For many years, military airfields utilized helicopter borne dry chemical fire fighting systems which would hover over fixed-wing aircraft approaching the field with a declared emergency that had the potential for an associated postcrash fire, such as a malfunctioning landing gear system with full fuel tanks. A study conducted by the U.S. Air Force covering a 10-year period demonstrated that, despite the close proximity of this fire fighting equipment, there was no improvement in human survival although it was possible to prevent complete fire consummation of the aircraft.

Studies at the Army Aeromedical Research Laboratory, Fort Rucker, Alabama, of helicopter borne fire fighting equipment of a different type were equally surprising. These tests evaluated a medium utility helicopter equipped with a swing-out boom and a directable nozzle which would spray a highly effective fire suppressant mixed with water to clear a path through the fireball. The helicopter also carried a heavily fire protected rescue man who would repel to the ground and theoretically run through the cleared path to extricate passengers. Even under the best circumstances with the helicopter fire fighting system at a hover one hundred yards away from the fire, at the moment of ignition of 50 gallons of fuel which had been allowed to percolate into sandy soil for one minute, the occupants of the fire would have perished. The rotor downwash from the fire fighting helicopter intensified the convective turbulence within the fire and caused ambient temperatures in the habitable fuselage to rise at alarming rates. The smoke and turbulence caused visibility problems for the pilot and for the rescue man once he made it to the aircraft. The fire fighting aircraft had to approach from the upwind side of the fire to avoid visibility and heat related turbulence problems. Depending on where he started his approach, this often cost extra precious seconds of delay. Although most fire fighting materials have proven effectiveness in reducing a fire's severity or putting it out, the problem comes in getting it to the fire in time.

It is well understood that most light utility aircraft accidents and helicopter accidents, especially those in the military that involve fire, occur off improved airfields and away from any significant fire suppression or rescue capabilities.

Survivors of combat, training, and incidental postcrash fires associated with Army military aviation operations for a two-year period were interviewed. The purpose of the interviews was to determine among other things the method of escape from the fireball. The survivors' responses could be categorized in three broad areas. First, the survivors thought that they had been thrown clear of the aircraft during the crash sequence. This was particularly true for passengers of helicopters that were flying with the cargo doors open. Second, the survivors were pulled or rescued from the aircraft by fellow passengers or crewmembers. Many survivors lived only to the peril and the sacrifice of a rescuer. Third, the survivors had no knowledge of how they escaped the fireball, attributing their escape to miracles, delayed fire onset, and largely unknown factors. There were many instances where individuals escaped essentially unharmed, only to be severely burned on returning to the aircraft to help someone else or to rescue first aid equipment or, ironically, fire extinguishers.

AUTOMOBILE RACING FIRES

Cameras and observers with stopwatches are rarely available at the instant of an aircraft postcrash fire. To better define and understand the worst-credible environment, we sought an analog to the aircraft fire and found it on the automobile racing circuit.

The similarities between automobile racing accidents and light fixed-wing and rotary-wing aircraft accidents are many. The crews, in general, use a full array of protective equipment from helmets to thermal protective suits. The fuel loads at the time of crash are often similar, although the types of fuels are widely different. The pilots of racing cars and aircraft use similar restraint systems that must be released. Escape from a race car and escape from a cockpit of a helicopter involve similar climbing, getting your bearings, and running to get outside the fireball. Impact forces at the time of crash can be very similar because of the similar impact velocities of the vehicles. Monocoque and tubular construction using light aluminum, aluminum magnesium alloys, and resin impregnated Fiberglas, as well as the proximity of fuel storage to the occupant(s) create additional similarities.

Track side motion picture photographers and photographers with motor driven 35mm cameras have inadvertently preserved valuable data for us to study to understand fire survival. At this time we will show you some film clips and picture sequences of postcrash automobile fires which are representative of worst-credible aircraft postcrash fire environments.

REDUCTION OF THE POSTCRASH FIRE HAZARD

Other lecturers during this series will discuss in detail the various aspects of fire reduction and fire prevention. From the human survival standpoint, the best way to reduce injury and eliminate death is to prevent fire in the first place. We have already discussed and pointed out the relative uselessness of fire fighting techniques and rescue to improve human survivability.

Fire Prevention

Fire severity, onset rate, and size can be dramatically altered by the use of fuels that have higher vapor pressures, high flash points, high viscosity or can be made to gel, or which can be inerted by the binary addition of inerting agents to the fuel cells at the moment of crash.

Fuel containment through the use of bladders, foam filled fuel tanks, as well as Fiberglas or nylon wrapping of external fuel tanks has been rewarded with some success.

Fire inerting systems using nitrogen atmospheres in fuel tanks or Halon in the passenger and crew compartments and in internal wing and fuselage compartments are at least theoretically feasible. These techniques have found usefulness in buildings, land fuel storage areas, and aboard tanker ships.

The elimination of ignition points, such as electrical sparks from broken high amperage electrical wires, and the elimination of ferrous metals on the aircraft fuselage that can cause sparks when the aircraft slides to a rest against rocks or concrete can reduce this hazard. Relays and switches that have the potential for creating sparks can be sealed or potted or exchanged for solid state devices. Attention paid to battery location with proper venting of hydrogen rich gases and battery cases with heat exchangers in the event of a battery over-heat might be profitable. Use of self-extinguishing alloys and composites in high risk areas of the fuselage has been considered.

Crashworthy Fuel System (CWFS)

In our opinion, the most significant advance to reduce the fire hazard has been the development of the crashworthy fuel system in common use in U.S. Army rotary-wing aircraft. Beginning in 1970, all new helicopters that were manufactured were equipped with a crashworthy fuel system. At the same time, an extensive retrofit program of older aircraft was begun and is now complete. The ideal crashworthy fuel system is one that completely contains its flammability both during and after the crash sequence. To accomplish this, all components of the system must resist rupture regardless of the degree of failure of surrounding structures. Success of such a system depends on proper selection of materials and design techniques in the areas of fuel tanks, fuel lines, and supporting components and subsystems such as valves. The ideal system would also reduce or eliminate potential ignition sources. The hydraulic system would be similarly protected or nonflammable hydraulic fluid would be used. Fuel tank location, fuel tank shape, and fuel tank materials will be carefully engineered. Tank fittings and tank attachments will be designed to shear or break away from associated structures without causing secondary damage. Valves will be self sealing. In some instances attachment strength to prevent breakaway will have to be increased to as much as 80 percent of the failure level of supporting structures. Fuel arms may have to be flexible and armored and coiled or wrapped to allow extension and distortion without rupture. Fuel line attachment clips will be breakaway and not cause secondary cutting or tearing of fuel lines. The routing of fuel and hydraulic lines requires design attention in the early stages of airframe layout. Passage holes through bulk heads that can distort and cut a line may need to be larger than normal. Supporting components play a vital role in that they should be capable of preventing spillage in accidents with crash forces equal to or better than tank strength. The fuel tank vents must prevent fuel leakage in the event of aircraft roll over. The same applies to fuel filler necks and quantity sensors found in the fuel tanks themselves.

Figure 8 shows the schematic of the crashworthy fuel system installed in the Bell UH-1D/H helicopter fleet. The basic features are the same in systems installed in other aircraft types. Figure 9 graphically demonstrates the system's effectiveness during a severe crash.

FIGURE 8. Schematic of the Crashworthy Fuel System Installed in the UH-1D/H Helicopter Fleet.

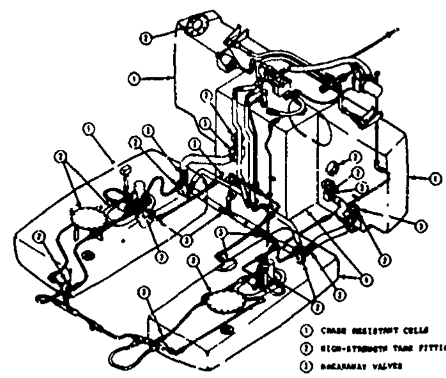


FIGURE 9. This UH-1H crashed at night in instrument meteorological conditions (IMC). The pilot and copilot survived with injuries. The CWFS functioned as designed. Note the right forward fuel cell in the foreground, which tore loose from the aircraft and prevented fuel spillage. There was no postcrash fire.

EPIDEMIOLOGY OF FIRE MORBIDITY AND MORTALITY

Aircraft accident survivability is a generic classification dependent upon habitable postcrash cockpit structural space and/or crash acceleration forces at the floor under the seat that are within human tolerance irrespective of the influence of fire or water (drowning). All aircraft accidents can be classified as survivable, partially survivable, or nonsurvivable. Because this classification does not consider the effects of fire, it is possible for an individual to survive the impact of a nonsurvivable accident and die a thermal death. The initial impression of lay persons or persons unfamiliar with postcrash accident analysis techniques when viewing the burned wreckage and victims of an accident is to make a wrong judgment that death was caused by fire. In fact, none of the victims may have died as a result of fire. All fire related injuries may be post-mortem.

Table II presents fatalities and injuries from 68 nonsurvivable accidents classified as to their thermal and nonthermal etiologies. No aircraft in this series were equipppped with crashworthy fuel systems.

TABLE II

1967-1969 FATALITIES AND INJURIES IN NONSURVIVABLE ARMY HELICOPTER CRASHES*

Aircraft	Fatalities		Injuries	
	Thermal	Non-Thermal	Thermal	Non-Thermal
UH-1D	64	108	2	8
UH-1H	31	148	1	0
AH-1G	1	14	0	0
TOTAL	96	270	3	8

*68 accidents, no crashworthy fuel systems, 57 postcrash fires

Table III presents the same data on 1,000 accidents classified as survivable. Elimination of fatalities and reduction of injury in survivable accidents are a more realistic goal than trying to make nonsurvivable accidents survivable. It should be noted that postcrash fires occurred in 13.3 percent of survivable crashes and contributed 95 thermal injuries or approximately 60 percent of the 159 fatalities in this series.

TABLE III

1967-1969 FATALITIES AND INJURIES IN SURVIVABLE ARMY HELICOPTER CRASHES*

Aircraft	Fatalities		Injuries	
	Thermal	Non-Thermal	Thermal	Non-Thermal
UH-1D	47	106	32	718
UH-1H	47	49	25	530
AH-1G	1	4	7	49
TOTAL	95	159	64	1297

*1000 accidents, no crashworthy fuel systems, 133 postcrash fires

Table IV dramatically demonstrates another series of accidents and the relationship of fire related injuries and death with and without the crashworthy fuel system. This series of accidents was taken during the 1970-1976 time frame when there were parallel developments in better crew restraint systems, more crashworthy seats, fire resistant aramid flight clothing, and fewer old high-fire-risk aircraft being flown. The 16 fires that occurred in aircraft equipped with the crashworthy fuel system resulted in five thermal injuries but no fatalities. These were early crashworthy systems that had some inherent flaw or deficiency.

TABLE IV

1970-1976 ARMY HELICOPTER CRASH FATALITIES AND INJURIES

Classification	Survivable		Nonsurvivable	
	w/o CWFS	with CWFS	w/o CWFS	with CWFS
Thermal Injuries	20	5	5	0
Non-Thermal Injuries	529	386	13	28
Thermal Fatalities	34	0	31	1
Non-Thermal Fatalities	120	44	229	85
Accidents	1160	1258	61	32
Postcrash Fires	43	16	42	18

Tables V and VI break down injuries and fatalities respectively for the same series of accidents. The majority of deaths and injury occur in UH-1H accidents. The UH-1H is not necessarily less crashworthy. It is the workhorse of the Army helicopter fleet and the most flown aircraft; thus, exposing it to the greatest accident risk.

TABLE V

1970-1976 INJURIES BY AIRCRAFT TYPE

Aircraft	Thermal		Non-Thermal	
	w/o CWFS*	with CWFS**	w/o CWFS*	with CWFS**
UH-1D	1	0	39	26
UH-1H	18	5	352	345
AH-1G	3	0	75	17
OH-58A	3	0	76	26
TOTAL	25	5	542	414

*1221 accidents, without CWFS, and 85 postcrash fires

**1290 accidents, with CWFS, and 34 postcrash fires

TABLE VI
1970-1976 FATALITIES BY AIRCRAFT TYPE

Aircraft	Thermal w/o CWFS*	Thermal with CWFS**	Non-Thermal w/o CWFS*	Non-Thermal with CWFS**
UH-1D	8	0	10	5
UH-1H	49	1	263	107
AH-1G	3	0	36	12
OH-58A	5	0	40	5
TOTAL	65	1	349	129

*1221 accidents, without CWFS, and 85 postcrash fires
**1290 accidents, with CWFS, and 34 postcrash fires

Since 1976, in Army helicopter aircraft equipped with crashworthy fuel systems involved in accidents classified as survivable, there have been no thermal related injuries or deaths. There have been postcrash fires, but because of the protective microenvironment provided to the aviators, they have been able to successfully escape without injury.

DESIGN CONSIDERATIONS FOR EFFECTIVE FIRE PROTECTIVE CLOTHING SYSTEMS

Thus far, we have defined the threat of fire, discussed the epidemiology of morbidity and mortality, and looked at the practical considerations of reducing injury and death by eliminating the fire itself and by providing personal protection. We now focus on the design of personal protective clothing systems. There are a number of factors to be considered in such a design process. Some of these factors relate to the protective quality of the clothing systems, while others relate to the acceptability or cost effectiveness of such ensembles.

Comfort

The first factor to consider is comfort. Comfort is subjective and based on many parameters, such as the feel of the fabric, the ability of the fabric to absorb or pull water away from the skin and evaporate it on the surface of the fabric, the suppleness or stiffness of the fabric, and its ability to breath or exchange air. As might be expected of such a subjective quality, comfort is difficult to measure, and there is much controversy surrounding the ways in which one designs comfort into fire clothing systems.

Bulk and Launderability

The next quality to consider is bulk. A bulky garment often makes it unacceptable, particularly in hot climates or in jobs which require considerable dexterity. Another factor is launderability. Any garment which is difficult to clean will be unacceptable to the user. User acceptability relates also to the ability to dye the clothing systems in acceptable colors. Dye selection must take into consideration the durability or fastness of the dye and considerations of the toxicity of dyes should they come off the fabric during normal wear or heating in a fire sequence.

Insulation, Permeability, and Durability

It is now possible to measure the insulative properties of a clothing system using instrumented copper manikins and calculate a clo value, or insulating value, for ensembles. From this value, the ability to operate in hot environments without causing heat stress can be calculated. Many synthetic fabrics do not wet; i.e., the amount of water that the fibers take up is essentially negligible as compared to wool or cotton and other natural fibers. However, some synthetic fibers can be constructed to transport water away from the skin by capillary action and evaporate that water at the surface of the garment thereby contributing toward comfort. The weave or construction of fabrics used in clothing systems will result in a certain air permeability of the fabric. The more permeable it is, the cooler the garment is likely to be. However, hot air from the fire will also tend to move through a fabric which has high air permeability. The durability of the fabric relates to such properties as abrasion and tear resistance of the fabric.

Layering

It has been shown by Stoll and confirmed by our own work that layering provides extra insulation from the effects of fire. As a rule of thumb, the more layers the more protection. The problem comes when one considers the acceptability of a garment for use in everyday wear in environments where more than one or two layers would be uncomfortably warm. Thus, there is a conflict between protection from fire, on the one hand, and comfort, on the other.

Fabric's Response to Fire

The final attribute, and the one upon which we will now focus, is the response of the ensemble to fire itself. Under this category, we will consider such things as flammability of the components and the maintenance of structural integrity of the fabric when subjected to the fire. We need to consider whether the fabrics shrink when heated or whether they char or ablate. And finally, we need to consider the amount of energy transferred through a fabric or a clothing system, because it is this transferred energy that interacts with the skin to form a burn.

Before we move on to the consideration of the response of protective ensembles to fire, let us review the problem of overall design. The design of any clothing system is essentially a compromise. It is not possible to provide maximum protection in a garment which is maximally comfortable. Comfortable garments tend to provide less protection than garments which are bulky and basically uncomfortable. Thus, there has to be a trade-off between comfort and protection. Often, there has to be a trade-off between cost and protection. The materials out of which protective ensembles are currently made tend to be difficult to dye. Therefore, the selection of colors may be hampered by the necessity of using certain polymers. By the same token, certain polymers may be excluded from consideration, because they cannot presently be dyed to meet user requirements. The essential point is that <u>every clothing system is a compromise</u>.

EVALUATION TECHNIQUES FOR PERSONAL FIRE PROTECTIVE CLOTHING ENSEMBLES

The evaluation techniques for fire protective clothing systems evolved out of the need to answer a number of questions. The first question relates to the flammability of individual components. Does a fabric burn when subjected to a hot source? This basic question arose out of the assumption that a fabric which did not burn when exposed to a fire source and would not sustain combustion upon the removal of this fire source would be a good candidate to include in protective clothing system designs.

<u>Flammability Tests</u>

Over the years a number of engineering flammability tests have been developed and standardized. One test utilizes flame impingement at the edge of a swatch of material. Each test specifies the type of flame or heat source, the length of time the flame touches the edge of the fabric, and the acceptability of a certain amount of fabric burning. In the edge burn test, the fabric tends to burn away from the flame. A self-extinguishing fabric will stop burning when the fabric is moved far enough from the flame. A flammable fabric will continue to burn until the fabric is consumed. Modifications of this approach include exposing the heat source perpendicular to the surface of the fabric and holding the fabric at some angle, such as 45 degrees, to simulate a combination of horizontal and vertical orientation. One can readily see that in a vertical orientation, the burning fabric tends to heat up the fabric right above it, whereas the horizontal orientation would tend to heat only the air above the burning location and not necessarily the adjacent fabric.

The first basic problem with these tests of flammability centers on the fact that the sources are not adequate representations of real aircraft fires. They, in fact, simulate the cigarette or match carelessly placed next to a fabric, such as one would experience in household or clothing fires. The other problem is that there is no relationship between the fabric flammability and the amount of skin damage that results when such a fabric is worn in a fire.

<u>Test Methodology and Instrumentation</u>

This brings us to the next step in test method development; that is, the use of instruments such as calorimeters to measure the amount of heat evolving from a fabric as it burns or smolders. It has been possible for quite some time to measure the heat evolved from burning fabrics. The critical inadequacy has been the inability to make statements concerning the human response to heat flux (x number of calories per square centimeter per second); i.e., the amount of energy evolving from a combustible source.

In an attempt to more accurately simulate an aircraft fire, the U.S. Navy and the U.S. Army developed what are commonly referred to as "Fire Pit Tests." In these tests, Fiberglas manikins (Figure 10) are dressed in ensembles and instrumented with maximum temperature sensors usually consisting of paper sensors impregnated with organic compounds which melt at specific temperatures. The fires in the fire pits are provided by burning an appropriate aviation fuel spread on the surface of a pool of water. The manikins are drawn through the raging fire at a specified speed to give either a three- or six-second exposure. This method suffers in that only maximum temperatures are obtained without any time history. The fires are spotty and ensembles can emerge unscathed. While this is realistic of a real fire in some regards, it falls short of exposing fabric ensembles in a reproducible way to a worst-credible environment. In addition, the Fiberglas manikin does not represent human skin. No valid judgments can be made about relative degrees of burn protection if these factors cannot be controlled.

In an attempt to make a correlation between maximum temperature sensors and actual burns, both temperature sensors and living pigskin were subjected to an identical thermal source. The problem here was that the thermal source was a carbon arc lamp of somewhat different spectral content than the fire. The carbon arc lamp has a reasonably constant output; the fire pit, on the other hand, is an extremely variable thermal source (See Figure 11). In fact, the variability of the fire pit was such that in order to make any statistical sense of the variability, some 35 or 40 paired suits had to be run through the fire pit in order to make any statistical comparison between the two kinds of suits.

In an attempt to develop a correlation between heat flux measurements or temperature measurements and damage to the skin, a variety of skin simulants were developed. The simulants consisted of compounds possessing thermal properties similar to those of skin whose temperature response, when exposed to the fire or the energy transmitted through a thermal protective covering, could be expected to be similar to that of skin or which could be mathematically correlated to skin. It was possible with the skin simulants to measure the temperature rise as a function of time and to show that certain fabrics or fabric combinations resulted in a diminished response of the skin simulant. Unfortunately, there was still no firm relationship between the temperature rise in the skin simulant and the resultant burn. Stoll spent many years working out an approach using skin simulants and using a model to convert the temperature rise in the skin simulants to an indication of threshold blister formation. Unfortunately, the skin simulants themselves only mimicked skin's response to a limited extent and were best suited to mild exposures. They would not accurately measure greater than second-degree burns. The thermal source did not properly simulate a postcrash fire except for temperature. The exposures were to a very even heat source for controlled periods of time so that the heat input to the fabric simulant and heat sensor was essentially a square wave. Anyone watching and comparing a test and an actual fire would realize that the thermal input to a clothing system within a fire would not be a square wave but a time varying flux.

FIGURE 10. Fiberglas Manikin

FIGURE 11. Fire Pit

Bioassay Technique

In an attempt to resolve some of the problems in the previous methods, a bioassay technique was developed. We selected domestic white pigs as an analog for human skin. The pigs were anesthetized and exposed to a simulated postcrash fire consisting of burning JP4 fuel. The fire was housed in a specially designed furnace (Figure 12). Furnace wall temperatures, fuel-air ratios, and convective flows could be controlled. Exposure was controlled by a water-cooled shutter system. Heat flux applied directly to the skin could be widely altered. Heat-proof templates containing six circular exposure holes protected the skin from all exposure except that desired. The resulting circular burn sites were in areas left unprotected as controls or covered by various fabrics of interest. Methods were developed to grade the level of burn from no burn to full thickness burn over 16 levels. Biopsies of the burn sites were accomplished, and measurements of the actual burn depth were made on these biopsies. In some instances small thermocouples were implanted within the skin to follow the temperature rise and fall during and after exposure to the thermal source. During some exposures we took highspeed motion pictures of blister formation. During these sequences we noted the shrinkage of the skin followed by the separation of the epidermal and dermal layers due to steam formation, the subsequent breakdown of the blister itself, and further charring of the protein. During these observations it became quite clear that any consideration of burn mechanism would have to take into account blister formation and the boiling of tissue water.

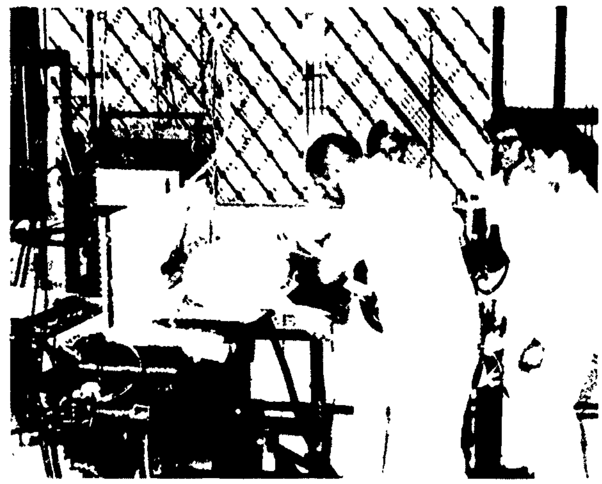


FIGURE 12. Furnace

It should be pointed out that in the earlier human volunteer studies of Stoll, the blisters that were formed were generally formed subsequent to exposure, i.e., the exposures were relatively mild. The human blisters were the result of accumulation of fluid at the epidermal-dermal boundary. Threshold blister was defined as the appearance of a blister within 24 hours after burn. The blisters which occurred in the more severe pig burns resulted from tissue water boiling and the sometimes explosive production of steam at the epidermal-dermal boundary. The difference in blister formation was largely due to the rate of heating. Until skin desiccation is complete, dermal temperatures remain at 100 degrees Centigrade.

The bioassay method had the advantage over previous methods in that actual burns were produced under test fabrics. This proved to be important in conveying to engineers and physicians biologically valid information which managers needed to make their selection decisions; i.e., would the samples protect the wearer from damaging effects of fire and if so, to what extent. The difficulty with the bioassay technique is that it is very costly and very time consuming. It is really not cost effective to screen potential new fabrics or fabric ensembles with the bioassay technique because of the number of people, the animals, and the cost involved.

Models of Burn Mechanics

The next step was to take heat flux sensors and measure the heat transfer through fabric systems with these sensors and to correlate the thermal transfer with the burns that would have been produced using the bioassay technique. A data base was built of more than 1,600 burns. The nonlinearity of the burning process, especially when you consider the complexity of tissue water boiling, blister formation, and the like, did not lend itself to a straightforward correlation between heat flux and tissue damage. The final step in the process, then, was to develop a mathematical model which would transform heat flux measurements into burn depth predictions. To develop this model, two approaches were taken. One was essentially a statistical approach using multidiscriminate analysis. This has the advantage in that it is reasonably easy to do once one has the sufficient information in the data base. There is a problem connected with this approach, however, which is that the statistical model may be valid only for the conditions under which the data were taken. The approach finally settled upon was to analytically model the situation. Our approach had its origins in the work of Moritz and Henriques at Harvard in the 1940's as extended by Stoll at the Naval Air Development Center; Mehta and Wong at the Massachusetts Institute of Technology; Takata, Illinois Institute of Technology, under contract to our laboratory; and finally by those in our own laboratory.

The approach we followed was to stick with the early assumption made by Moritz and Henriques that damage proceeds as essentially a first order chemical reaction related to the temperature of the tissue. The idea is that if one can predict or measure the temperature of the tissue, one can calculate a damage rate based on that temperature using a first order equation. The procedure is to adjust the coefficients and exponents of the first order equation such that the integral of the damage rate over the time course of the burning process is equal to one (1) at a depth judged to be the transition between normal and abnormal tissue. Stoll took this process one step further and considered not only the heating phase but the cooling phase of the burn process as well. In this earlier work there seemed to be a threshold beyond which tissue was damaged and below which repair either equaled damage, or no damage was occurring. This threshold temperature is variously quoted as 44 or 45 degrees Centigrade. Stoll's exposures were relatively mild, up through 0.4 calories per square centimeter per second, and were a great deal less than the exposures seen in an aircraft fire. In engineering terms, she was essentially using small signal linearization. She adopted this strategy because she was interested in threshold blister as a cutoff and was constrained by human reaction time to use exposures sufficiently mild to allow subjects to remove their fingers from the heat source prior to severe burn. The response of the tissue during these relatively mild inputs did not respond with such disruptive phenomena as massive blood flow changes or blister formation during the course of the burning process; hence, her model worked only for relatively mild inputs.

When the model was applied to some of the more severe inputs contained in our data base, it was found to over predict the damage. In studying the problem in some depth, we determined that several changes had to be made. First, the model had to take into account water boiling in the formation of a blister. Takata included this in his model for us. Second, the flow of heat had to proceed through the skin and into deeper layers of the body, because sufficient energy was entering the system to bring the temperature of the entire system above damage threshold. Without the flow of energy out the back wall, this skin model would be completely damaged at inputs which actually caused much less injury. Third, for long, severe exposures, changes in blood flow had to be taken into account. Fourth, changes in thermal properties of skin after blister formation and desiccation of the surface layers had to be taken into account. Fifth, a profile of thermal properties as a function of depth had to be introduced, and it was found that by measuring tissue water, it was possible to develop a correlation between tissue water and thermal properties which allowed for a thermal properties profile to be developed and modified as the tissue water was boiled off. The resulting outputs of our model, BPNSIM, which can be seen in Figures 13 and 14, not only fit porcine or pig data quite well but also fit human data of the small signal variety derived from Stoll's experiments.

FIGURE 13. Model Output Simulating Porcine Burn Data.

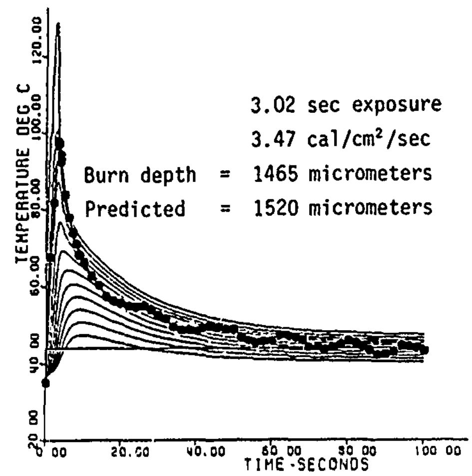
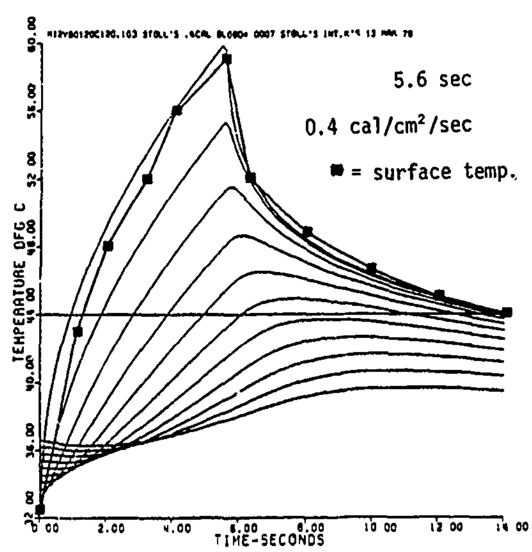


FIGURE 14. Model Output Simulating Stoll's Human Data.



We now have a model which predicts burns quite accurately from very mild to full thickness and in doing so takes into account blistering, flow of heat through the skin into a deep core reservoir, thermal properties of the skin and changes to those thermal properties, and in a very rough sense circulatory changes in the skin. It is beginning to be possible to relate burn depth to clinical prognosis. As that relationship firms up and as the model just described is perfected, it should ultimately be possible to make a reasonable prediction regarding survival wearing a given ensemble in at least a standardized fire.

Let us now turn our attention to the protective performance of selected fabrics and ensembles as assessed using the aforementioned techniques.

PROTECTIVE PERFORMANCE OF SELECTED FABRICS AND ENSEMBLES

Underwear

The first consideration is the use of long underwear under an outer shell garment. Some years ago we were asked to assess the feasibility of using Nomex® underwear ("long john" underwear) under flight suits as an extra protective layer. We ran parallel samples of outer shell fabric with and without underwear using our bioassay technique. As a control we selected standard 50 percent cotton, 50 percent wool "long john" underwear. Much to our surprise and certainly to the Nomex® fabric developer's surprise, the 50 percent cotton, 50 percent wool underwear performed as good or better than the Nomex® underwear up to seven seconds of exposure. There was considerable cost savings in continuing to use the 50 percent cotton, 50 percent wool underwear. Out of these early studies and observations, we not only developed the bioassay technique, but we began to realize what Stoll had realized some years ago; namely, that layering was extremely important in providing thermal protection and that any extra layer goes a long way toward providing much needed additional thermal protection. The exact relationship depends on the fabrics involved, but it is safe to say, we think, that one additional layer is more than twice as good in protecting the wearer from the effects of the fire. It was also clear that there is an interaction between the fabric layers depending on the spacing between the layers. If an outer fabric is touching a layer, the underlayer tends to protect the outer fabric by pulling heat away from the fabric itself. On the other hand, if there is a space there tends to be less thermal transfer through the total system, but the outer fabric tends to degrade more rapidly. If the space is too large, the insulating effect and the ability of the outer layer to maintain its integrity are both lost.

Field Observations

Simultaneously and concurrent with the laboratory studies on underwear and layering phenomena in reducing burns, the Aeromedical Research Laboratory at Fort Rucker, Alabama, was evaluating the relationships between actual human burns and the fire protective garments, boots, gloves, and helmets being worn. Noteworthy findings included several accidents where an individual was exposed to a significant thermal threat either in the form of an in-flight fire or a postcrash fireball and where the thermal protective flight suit was not significantly damaged and yet the person died of burns. On closer examination it was obvious that certain design deficiencies occurred in the early fabrics used for thermal protective flight suits. If a torn garment is repaired with cotton thread instead of a thread made from the same material used in the basic fabric, the thread will burn when exposed to fire. As the fabric shrinks it will split open exposing skin. We also found that improper sizing of the garment contributed to injury. If the wearer had become overweight since the garment was fitted or if the garment were too small in the first place and then exposed to fire, the normal shrinking process would bring the hot and charred garment in direct contact with the skin resulting in direct conductive transfer of heat. The uniform was prone to split as further shrinking occurred. The shrinkage problem in loose fitting garments had its advantages in that as it folded, the relatively open weave of twill or knit fabrics would close offering a better ablative shield. Our laboratory studies and field accident experience demonstrated the clear advisability of maintaining at least a quarter of an inch air layer between the fabric and skin.

In the early years of thermal protective fabrics, the uniforms were often made in two pieces. If the shirttail were too short or if during the flight the shirttail worked its way out of the pants and the individual was exposed to a postcrash fire, there was an increased potential for serious burns on the torso, neck, and face. As the shirt would come out of the pants, an effective chimney would be formed causing large convective currents to flow under the shirt to exit through the neck opening. These hot gases would then flow into the open areas of the helmet causing severe burns on areas of the head normally shadowed by the helmet from radiant heat sources. Improper use of gloves and boots was also found to contribute to poor survivability. Leather is without question one of the best thermal protective fabrics known, even with its considerable shrinkage problem. The use of heavy leather boots as contrasted to boots with light nylon or nylon-like inserts is to be recommended. Hand burns are extremely difficult to treat and have a prolonged recovery time. It is not uncommon to lose considerable function and dexterity of the hands after the burn. The use of leather and leather Nomex® gloves that are long enough to cover the sleeves is warranted. Thermally protective fabrics, because they are synthetic polymers, tend to be cooler in cold weather and hotter in hot weather than wool or cotton. While flying in cold climates, people will often choose underwear that has extra insulative values such as quilted Dacron or other synthetic man-made fibers. These types of underwear and the basic materials from which they are made have very low melting points. Postcrash heat transfer through a thermally protective garment can melt the underwear without igniting it, causing fatal burns with essentially no destruction of the outer garment.

Fabric Comparisons

The polymer industry has discovered a whole series of new molecules which are formed into fibers and later woven into fabrics that offer thermal protection. They include, but are not limited to, aramids, mylar plastics that are gold plated to reflect heat, various designs of glass fabrics, asbestos, heat stabilized nylon, spun bakelite, treated wools and cottons, polybenzimidazole, and fabrics made up of a combination of any one of these plus metallic threads. But, as we have stated earlier, the final decision regarding a fabric for use in an ensemble is at best a compromise. For example, glass fabrics have a high degree of thermal resistance but are of limited durability and dye poorly. Polybenzimidazole is available only in limited supply and is very expensive, while the common and less expensive aramid fibers offer some recognized comfort problems and less thermal resistance.

What we present now is a comparison study of four compromise synthetic materials in varying fabric configurations and standard cotton undershirt material.

As can be seen in Table VII, these four fabrics had somewhat varying textile properties. As can be seen in Table VIII, the fabrics singly or in combination with normal cotton underwear provided various levels of protection with the more stable polymers combined with underwear providing the most protection. These fabrics were assessed using the bioassay technique. As can be seen by Figure 15, various levels of burns were experienced. These same four fabrics were also evaluated using thermal sensors so that these data could be used to fine tune the aforementioned model, BRNSIM. The correlation between the output of BRNSIM and the observed burns using the same fabrics discussed above is found in Table IX. As you can see, there is a very good correlation between the observed and predicted burns over a wide range of very shallow to very deep burns. We also learned during these studies that the fiber and dye degradation products (FDP) which off gas as the fabric is heated condense on the surface of the skin but usually wash off with very little effort. Such deposits can be seen in Figures 16 and 17. Our very preliminary study of these fire degradation products showed that they do not interfere with wound healing nor will they appreciably alter the degree of burn which one sees. The FDP are apparently trapped on the surface of the skin and do not penetrate significantly.

TABLE VII
FABRIC CHARACTERISTICS

Fabric	Weave	Weight* (oz/yd^2)	Thickness** (inches)	Air Permeability*** ($ft^3/ft^2/min.$)
Nomex Aramid®	Twill	4.8	.016	181.5
Polybenzimidazole	Twill	4.5	.014	171.0
Experimental High Temperature Polymer (HT4)	Plain	4.8	.010	12.8
New Weave Nomex Aramid®	Plain	4.6	.008	28.1
T-Shirt	Jersey Knit	4.8	.023	152.5

*ASTM Methods D1910-64, D231-62.
**ASTM Method D1777-64.
***ASTM Method D737-46.

TABLE VIII
MICRO-GRADE DEFINITIONS

Grade	Definition
0	No thermal damage
1	Cell damage without acidophilism
2	Epidermal acidophilism (partial)
3	Epidermal acidophilism (complete)
4	Dermal-epidermal separation (partial)
5	Dermal-epidermal separation (complete)
6	Dermal superficial <500μ
7	Dermal mid 500-1000μ
8	Dermal deep 1000-1500μ
9	Dermal complete 1500-dermal/adipose border
10	Adipose

TABLE IX
CORRELATION BETWEEN BRNSIM PREDICTIONS AND OBSERVED BURNS

Test No.	T_o	Exposure Time(s)	Fabric	T_D+ Obs. (μm) Normalized	Corrected	T_D Calc. (μm) Model II	Model* III_A	Model** III_B
Sim 21208	31.8	2.97±.02	NWN	129	147	<222	99	252
Sim 21213	32.2	2.97±.02	AFN	237	296	222-444	0	87
Sim 31208	31.8	2.97±.02	PBI	152	201	565	54	143
Sim 31213	32.2	2.97±.02	HT4	62	59	563	49	141
212,36,11	29.8±1.2	4.97±.02	AFN	968±508	1200±529	973±541(3)	689±81	1031±92
28,33,39	31.3±0.8	4.97±.02	PBI	766±361	943±453	757±194(3)	761±190	1049±196
23,27,29,211,310	30.0±1.8	4.97±.02	HT4	847±633	945±650	626±144(5)	561±239	884±295
26,210,37,38,312	29.7±1.7	4.97±.02	NWN	866±500	1043±549	756±47(5)	799±41	1131±36

+ T_D = Threshold Depth - mean ± 1 S.D. (N)
* Heat Flux, Q, = Q absorbed by sensor with skin absorptivity = .60
** Heat Flux, Q, = Q incident to sensory with skin absorptivity = .64

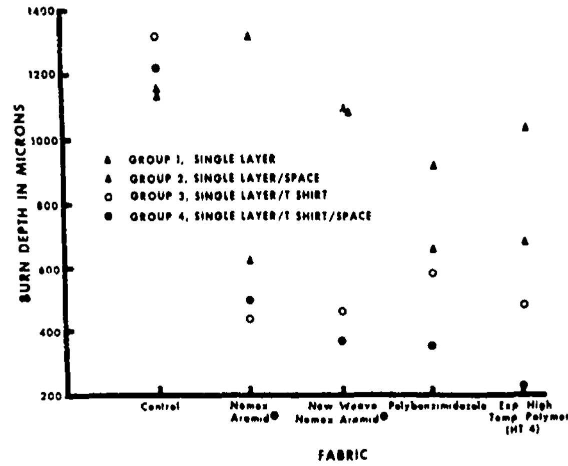


FIGURE 15. Mean Depth of Burn in Microns for Each Fabric/Configuration.

FIGURE 16. Visible FDP is deposited on the steam bleb and not on the underlying burned dermis.

FIGURE 17. Photomicrograph (X50) of FDP as it appeared on an unstained frozen section. The separation is artifact. Arrow 1 points to the dye layer, and arrow 2 points to the epithelial layer.

CONCLUSIONS

We think several things can be concluded from what we have been able to present today. First, aircraft fire poses a major threat to human survival. The threat comes in the form of smoke, toxic gases, and the fire itself. The materials used on board modern aircraft tend to produce very toxic compounds when heated to ignition or just short of ignition. The quality of the smoke in such fires is such to prevent efficient escape from the aircraft and would be toxic to those who remain behind. Aircraft fires are sufficiently hot and of sufficient magnitude as to cause catastrophic burns. In light rotary-wing aircraft, for example, escape must be effected within the first few seconds after ignition of a fire in order to result in any chance of survival. The worst credible but survivable environment in a helicopter fire is about 2100 degrees Fahrenheit or four calories per square centimeter per second. These fires typically build up to full magnitude within the first 20 seconds and last for many tens of seconds beyond that time, depending on the quantity of fuel available. The build-up would be considerably faster in cases where there is misting of fuel creating an explosive atmosphere. The introduction of crashworthy fuel systems and crashworthy design features in aircraft such as the Sikorsky UH-60 Blackhawk and good thermal protective equipment has resulted in a marked reduction in the death and injury due to aircraft fires. Many of our civil aircraft do not have such crashworthy fuel systems. Short of preventing the fire, the next preventive measure is to provide the passengers and aircrew with protective ensembles which would allow them to escape through the fire without undue thermal injury. We have considered the factors which must be taken into account in the design of such protective ensembles, and we have focused on the measurement of fabric flammability and, to an even greater extent, on the measurement of thermal transfer through the fabric ensemble to the skin and the resulting tissue damage. Over the years it has been possible to move from very simplistic measures of thermal transfer to a computer model which now will take heat flux as a function of time and convert that to a predicted burn depth. Predicted burn depth when combined with new epidemiological data concerning morbidity and mortality give us some as yet imperfect measures of survivability. We now have the test methods available to rapidly screen fabrics and combinations of fabrics in ensemble form to reach the goal of providing adequate thermal protection for aircrew and passengers. As always, the important thing to be emphasized is <u>prevention</u>. The best course is to prevent the fire, and if the fire cannot be prevented, then to prevent the burn. The burn injury is perhaps the most devastating injury that can be sustained by the human body. Its treatment is the most costly; its recuperation, the most prolonged; and the agony, the most profound. Great strides have been made in recent years in the treatment of burn injuries, both the physical treatment and the psychological treatment of the victims and their relatives. We can save lives of many who would have been lost five or ten years ago. But even these successes would pale in insignificance if we could prevent the injury itself.

Disclaimer

Acknowledgment

The authors are indebted to our many colleagues and to dozens of other investigators who have devoted so much of their own professional lives to save the lives of others. They are not forgotten, and although we have taken the liberty of not providing extensive references in the body of this lecture, we will make available a complete annotated bibliography for all those who desire. We are indebted beyond words to Ms. Jan Bailey who has over the years converted so many drafts of imperfect spelling and grammar into those finished manuscripts that go to press. Even if our writing is incomplete and flawed, her technical ability with the typewriter, dictionary, and camera-ready paper is not.

AVIATION FUELS-FUTURE OUTLOOK AND IMPACT ON AIRCRAFT FIRE THREAT

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SUMMARY

The properties of current aviation turbine fuels with respect to aircraft fire safety are described. Current projections of the availability of petroleum crudes indicate that specifications for aviation turbine fuels may have to be modified in order to use fuels produced from shale oil, heavy oils and coal. Projections of the chemical and physical properties of future aviation fuels produced from these alternative sources are discussed and compared with present fuels. Progress on programs to develop fire safe fuels through the use of antimisting additives is also described.

INTRODUCTION

Fire and explosion have been a continuing threat to aircraft, crew and passenger survivability. Although a variety of fire hazards are present on aircraft - materials, hydraulic fluids, and lubricating oils - the major threat is associated with the hydrocarbon fuel in view of its large quantity and dispersed storage. During the past 20 years, considerable effort has been devoted to determine the relative safety advantages of different types of aviation turbine fuels through both laboratory tests and large-scale aircraft simulation tests.

Currently, aviation consumes a relatively small proportion of the total energy used in transportation and of the total petroleum products. For example, aviation turbine fuels account for about four percent of the petroleum barrel in Europe and about seven percent in the United States. Potentially, at least 12 percent of the barrel can be made into specification jet fuels by conventional refining processes. In the U.S., demand for transportation fuels has dropped in the past two years and this trend is expected to continue through the 1980's. The demand for aviation turbine fuels is expected to increase at about 1.7 percent annually. Most current fuel supply-demand forecasts indicate there should be sufficient liquid hydrocarbons available through the year 2000, unless military or political crises occur.

Since 1974, the cost and availability of aviation turbine fuels, as well as other fuels have drastically changed. In the case of jet fuels, costs have increased by a factor of ten for both commercial and military consumers. During certain periods, fuel shortages have occurred even though conservation measures have been accomplished and fuel demands have been reduced from 1973 consumption levels. These developments have encouraged research and development programs to determine the feasibility of producing jet fuels from other sources, such as coal, oil shale and tar sands.

Many nations are currently conducting research and development in at least one of these alternative areas. The U.S. has evaluated coal, oil shale and tar sands, Canada has concentrated on tar sands, and Germany, France and the United Kingdom have primarily considered coal. Throughout the 1980's, development of these technologies will expand, and by the 1990's, many countries will have in operation significant numbers of plants for the production of liquid and gaseous fuels from coal, oil shale, tar sands, peat and biomass.

The purpose of this technical paper is to discuss the flammability properties and relative safety of present aviation turbine fuels and the projected properties of future fuels produced from oil shale, coal and tar sands, as well as antimisting aviation turbine fuel, liquid hydrogen and liquid methane.

CURRENT JET FUELS AND FUEL PROPERTIES

Military Fuels

The history of aviation turbine fuels dates back to 1944 with the introduction of JP-1 as a military fuel. This -58°C freeze point fuel, having a 149°C to 260°C boiling range, could not be produced in sufficient quantities to meet military requirements. In an effort to increase availability, a wider cut fuel, JP-2 was authorized in 1945. JP-2 was used only for experimental purposes as viscosity restrictions limited its production. The availability problems posed by JP-1 and JP-2 resulted in the adoption of JP-3 in 1947. JP-3 was produced by blending gasoline with kerosene. Although this fuel was readily available, the relatively high Reid vapor pressure of 7 psi caused excessive losses in the order of 20 percent by venting of liquid and vapors in high rate of climb aircraft and at high altitudes. For these reasons a specification for JP-4, which essentially is a low vapor pressure JP-3, was issued in 1951 and at present is the standard military aviation turbine fuel for most of the NATO countries. The specification for JP-4 (NATO Code F-40) was defined at a time when this product was both inexpensive and plentiful. While there have been refinements to the fuel specification to keep pace with engine developments, JP-4 has basically maintained the critical properties first specified to insure availability and to fulfill aircraft operational performance requirements.

JP-4 is a wide-cut mixture of heavy naphtha and kerosene with an average boiling range from 61°C to 239°C. It possesses a maximum freeze point of -58°C and a Reid vapor pressure of 2 to 3 psi at 38°C. Related to the volatility is an expected low flash point of approximately -29°C and an explosive range from approximately -29°C to +21°C under equilibrium conditions.

The need for a less fire-hazardous fuel aboard aircraft carriers was responsible for the adoption of JP-5 (NATO Code F-44) by the U.S. Navy in 1952. It is considered the standard aviation turbine fuel aboard aircraft carriers within NATO. Properties of JP-5 affecting ignitability are a boiling range of 182°C to 258°C, a maximum freeze point of -46°C and a flash point of 60°C minimum. The narrow boiling range of JP-5, combined with the 60°C flash point requirement and -46°C maximum freeze point, are severe limitations in the production capability of this fuel.

Efforts to evaluate the use of a safer fuel than JP-4 for combat operations, as well as ground handling, were intensified in the U.S. starting in 1967. Combat losses directly related to fuel fires or explosions during the Southeast Asia conflict supported the basis for evaluation of a more combat-safe fuel. JP-8 (NATO Code F-34), which is essentially commercial Jet A-1 with fuel system icing inhibitor and corrosion inhibitor added, was selected for extensive testing in 1967. Initially considered as a possible replacement fuel for JP-4 in Southeast Asia, its expanded use for military application worldwide has been proposed. Significant and favorable volatility properties of JP-8 are a vapor pressure of 0.10 psi at 38°C and a minimum flash point of 38°C which normally exceeds ground handling temperatures. Several countries throughout the world use JP-8 (NATO F-34) as the standard military fuel instead of JP-4 (NATO F-40). These include France, Portugal, United Kingdom, Australia and New Zealand.

In the mid 1970's, efforts were started and are continuing to make JP-8 the standard fuel of the NATO air forces in Europe. As a service test, U.S. Air Force bases in the United Kingdom completed conversion to JP-8 in August 1979; U.S. Air Force operating units have reported no adverse impact on aircraft from continuous use of JP-8. Conversion from JP-4 to JP-8 in NATO Europe has been delayed due to concern of some nations over the higher cost and availability of JP-8 as compared to JP-4. At present, JP-8 is somewhat more expensive than JP-4. A recently completed NATO International Staff study concluded that availability should be no problem if the petroleum industry is given two years advance notice of the planned conversion date. The study was not able to resolve the cost issue, but has recommended that NATO set a conversion start date of January 1985. Formal national positions on this recommendation are due to NATO in early 1982.

Commercial Fuels

In 1951 the American Society for Testing and Materials (ASTM) formulated commercial jet fuel specification, ASTM D-1655. The requirements for Jet A and Jet B were specified at that time. Most of the commercial airlines used Jet B in the early days of the jet aircraft, but changed to the kerosene-types (Jet A and Jet A-1) over the years to enhance ground and flight safety. A few airlines continue to use Jet B because of availability problems producing Jet A-1, but the majority of commercial aviation carriers use Jet A-1, with the exception of the United States, who uses Jet A.

Properties of Jet A include a 38°C minimum flash point requirement and a freezing point of -40°C. Jet A-1, having identical properties to Jet A, except for a -50°C freezing point requirement, was added to the commercial specification in 1959 for use in long-range, high-altitude aircraft operations. In order to increase the availability of Jet A-1 worldwide, both the ASTM specification and the IATA (International Air Transport Association) Guidance Specification were changed in 1981 to permit a -47°C maximum freezing point.

FLAMMABILITY AND IGNITION PROPERTIES OF JET FUELS

Numerous technical papers and reports exist on the fire properties of jet fuels and the safety advantages of kerosene versus wide-cut fuels (1-6). Typical flammability and ignition properties of current aviation turbine fuels are summarized in Tables I and II.

The three main volatility characteristics relating to flammability are vapor pressure, distillation and flash point. Volatility is the tendency of a fuel to change from liquid to vapor and is the major property that affects its ability to vaporize and form a combustible mixture with air. Volatility not only affects the flammability hazards of the fuel, but is extremely important to the engine and fuel system designer since it affects vapor and entrainment losses, fuel pumpability characteristics and engine starting characteristics.

Fuel volatility is controlled in fuel specifications through vapor pressure in the case of JP-4 and Jet B, distillation in all fuels, and flash point in all fuels except JP-4 and Jet B. As shown in Table 1, the wide-cut fuels, JP-4 and Jet B, are much more volatile than the kerosene-type fuels; JP-4 and Jet B have much lower initial boiling points and flash points, and higher vapor pressures.

Vapor pressure is defined as the pressure exerted by the fuel's vapors in equilibrium with the liquid at a specific temperature with the absence of air in or over the fuel. For a pure hydrocarbon the vapor pressure is dependent only on temperature, increasing with increased temperature. For hydrocarbon fuels, which contain several hundred hydrocarbons with different boiling points, the vapor pressure will depend on the relative concentrations of these hydrocarbons and on the V/L ratio (ratio of the volume of vapor in equilibrium with a unit volume of liquid fuel).

The initial boiling point and lower boiling fractions of a fuel are closely related to both vapor pressure and flash point. As shown in Figure 1, the distillation curve of wide-cut fuels, JP-4 and Jet B, includes both aviation gasoline and kerosene fractions.

The flash point of a fuel is the minimum temperature at which its vapor pressure is sufficient to form a flammable vapor/air mixture at atmospheric pressure. The measured flash point closely parallels the lower limit of flammability below which vapor/air mixtures are too weak for combustion. Wide-cut aviation turbine fuel specifications do not include a flash point requirement, since values are normally below -20°C.

Other typical flammability and ignition properties of current aviation turbine fuels are summarized in Table II. With the exception of heat of combustion, these additional properties are not specification requirements, but are important fire properties of the fuels.

The net heat of combustion of a fuel is the heat released in burning a unit weight of fuel with the resulting products of combustion being carbon dioxide and water in the gaseous phase. The net heat of combustion per unit weight is an important factor in aircraft performance. The net heat of combustion per unit weight of all aviation turbine fuels is very similar, decreasing slightly with increasing density. In contrast, the heat of combustion per unit volume increases with increasing density of the fuel. Increased volumetric heat contents relate to increased aircraft and missile ranges.

Flammability limits are related to the volatility characteristics of fuels and are defined as maximum and minimum combustible gas in air concentrations which are capable of propagating flame. The lower (lean) limit is the point of fuel deficiency while the upper (rich) limit is the point of oxidizer deficiency to sustain combustion. These limits are dependent upon temperature and pressure. The flammability range is defined as a scale of mixture ratios between the upper and lower flammability limits. Curves of the upper and lower flammability limits for various aviation turbine fuels under equilibrium conditions are presented in Figure 2. The actual flammability limits which may exist under dynamic conditions will be significantly different due to the formation of sprays and mists during refueling and flight operations. Figure 3 depicts the change of the equilibrium limits due to these dynamic conditions. The mists can cause a significant expansion of the temperature at the lean limit only. The rich limits are not affected since dynamic situations only add fuel vapors or mists to a rich condition.

The minimum energy required for the ignition of fuels under ideal conditions is 0.2 millijoules. The minimum energy requirements for all aviation turbine fuels are the same. As conditions depart from ideal, such as the formation of fuel mists, sprays and foams, the ignition energy requirements increase. The minimum ignition energy for sprays of aircraft fuels are shown in Figure 4. It is shown that the ignition energy required to ignite a wide-cut fuel at 0°C is about 6 millijoules as compared to about 40-50 millijoules for kerosene fuels. The extra energy required for kerosene mists or sprays is due to the need to provide energy for vaporization of the liquid droplets.

The autoignition temperature of a fuel is defined as that temperature at which a fuel will ignite when vaporized on a hot surface at atmospheric pressure even though an external source of ignition is not present. The minimum autoignition temperature of all aviation turbine fuels is very similar. In contrast, the autoignition temperature of aviation gasoline is about 200°C higher than the wide-cut or kerosene fuels.

As shown in Figure 5, the flame spread across the liquid surface of a wide-cut fuel at temperatures above -18°C are much more rapid than across kerosene. For example, at 27°C the flame spread rate of wide-cut fuel is about 225 m/min as compared to about 7.5 m/min for kerosene fuels.

FUTURE FUELS

During the past few years several reports and journal articles have been written regarding projected properties of future aviation turbine fuels and their impact on cost, availability, aircraft engines and fuel systems (9-12). Projected changes in petroleum-derived fuels, projected properties of jet fuels derived from shale oil, coal and tar sands, development of antimisting kerosene, and nonhydrocarbon fuels will be discussed in this section.

Projected Changes In Aviation Turbine Fuel Properties

Concern for price, availability and safety of aviation turbine fuels and the introduction of lower grade, heavier crudes have resulted in both the U.S. military and NASA conducting programs to determine the feasibility of using broadened-specification fuels in both current and future aircraft engines and fuel systems, and to identify alternate fuels, such as shale-derived fuels that can be used in existing equipment. For current aircraft, it is important to establish the degree to which fuel properties may be varied without resorting to costly equipment modifications or having to accept significant reductions in service life and safety or increases in fuel consumption. These programs have involved, and will continue to involve, extensive research and development in the areas of fuel analysis, combustion effects, fuel system effects and overall fuel property/aircraft system trade-off studies. These programs have included a full range of component testing and full-scale engine evaluations (13-20) and will be followed by flight tests and finally, operational validation at various locations.

The properties of jet fuels with the greatest impact on availability and price are flash point, vapor pressure, freezing point and final boiling point. For example, a study conducted by Bonner and Moore Associates under a U.S. Air Force contract (21) indicated that for kerosene-type fuels, increases of 20 percent could be realized by relaxing freezing point and final boiling point, and increases of about 28 percent could be realized by relaxing aromatics, smoke point, freezing point and final boiling point together. For naphtha-type jet fuels (JP-4/Jet B), an increase of 24 percent could be achieved by increasing freezing point and final boiling point.

It should be noted that relaxing jet fuel specifications may not necessarily increase availability of jet fuels, as other fuels in that boiling range would be competing in the market place. For example, increasing the final boiling point of the kerosene-type fuels, Jet A/Jet A-1/JP-8/JP-5, would decrease the availability of diesel fuels and heating oils, as shown in Figure 6. The boiling range of JP-4/Jet B falls within that of both gasoline and the middle distillates, and thus, widening of the boiling range would impact availability of both gasoline and all the other middle distillate fuels. Note that JP-4 is largely blended from gasoline fractions and kerosene, while the other jet fuels share mainly the distillation range of diesel fuel and heating oils.

Many jet fuel properties are inter-related and in changing one specific property, other properties also change. An increase in final boiling point generally leads to increased aromatic content, decreased hydrogen content, decreased volatility and increased viscosity. A decrease in initial boiling point will reduce flash point, decrease viscosity and increase fuel flammability.

The two most significant trends in jet fuel properties over the past ten years has been the steady increase in average aromatic content and freezing point. This has resulted from increased use of heavy Arabian, Alaskan and North Sea crudes. These trends are expected to continue as more quantities of these crude sources are produced, unless processing equipment is installed either to extract aromatics or hydrogenate them to saturated compounds (paraffins and naphthenes).

The U.S. Air Force Aviation Turbine Fuel Technology Program is expected to result in minor fuel specification changes by 1983; however, for the most part will be similar to the present JP-4 and JP-8 specifications. By 1989, the program is expected to lead to significant fuel specification changes with the properties approaching those shown in Table III (12).

Results from NASA's program have also indicated that some relaxation of the current specifications may be needed to minimize the adverse impact on cost and energy consumption (11). Major fuel properties that could be affected by such a relaxation are shown in Table IV.

As shown in Tables III and IV, the only projected fuel property possibly affecting safety is the reduction of JP-8 flash point from 38°C to 32°C. A research program is currently underway by Southwest Research Institute under sponsorship of the FAA (Federal Aviation Administration) to explore the effect that a reduction in flash point from 38°C to 32°C would have on the safety characteristics of jet fuels and to determine the impact on misting characteristics when using an antimisting additive.

Antimisting Kerosene

During the past 15 years considerable research and development has been performed in the United States and the United Kingdom to develop modified fuels for reduction of the post-crash fire hazard. Specific approaches have included gellation and emulsification, incorporation of halogenated flame inhibiting additives, and incorporation of antimisting additives. Results of these programs have shown that any practical fire safe fuel concept must utilize a low volatility fuel, such as Jet A, Jet A-1 or JP-8 as the base fluid and must not drastically alter the compatibility, fluidity and low temperature performance characteristics associated with aircraft fuel systems and engine operating requirements.

Reductions in misting characteristics have been found by gelling or emulsifying fuels, but these methods are severely lacking in other critical aspects such as holdup of fuel in the aircraft tankage and pumpability problems. The antimisting additive approach appears very promising and is being pursued in a cooperative manner by the United States Federal Aviation Administration (FAA) and the United Kingdom under a Memorandum of Understanding (MOU). The antimisting quality is imparted to the fuel by the addition of low concentration in the order of 0.3% by weight of shear-sensitive hydrocarbon polymer. The additive currently being evaluated is known as FM-9 produced by Imperial Chemical Industries, Limited in the United Kingdom. This additive has been shown to be effective in reducing flame propagation through mists of kerosene fuels. These mists are generated by the high shear rate expulsion of fuel from a small tank opening or by air shear breakup of larger masses of fuel expelled during deceleration. Preventing the rapid development of a large fire around an aircraft involved in an impact survivable accident where fuel tank rupture occurs can allow more time for passenger and crew evacuation and result in a higher rate of survivability in this type accident.

The FAA's Special Aviation, Fire and Explosion Reduction Advisory Committee (SAFER) Report (22) concluded that fully developing the antimisting kerosene (AMK) technology could prove to be the single, most significant safety improvement to reduce the post-crash fire hazard. As a result of past research and development programs, the FAA believes that an antimisting additive is technically feasible and can provide increased protection against the post-crash fuel mist fire.

Conclusions of the two years of research and development under the MOU were that the use of antimisting fuel in the form of FM-9 at a concentration of 0.3 percent by weight in kerosene aviation turbine fuel gives the promise of significant fire protection in post-crash situations where a fireball could exist. The second conclusion was that although there are problems, no insurmountable technical problems are envisioned at this time. Details of these programs were presented at the Aircraft Research and Technology for Antimisting Kerosene Conference on February 18-19, 1981 at the FAA Technical Center (23).

As shown in Table V, the major problems or concerns include the fuel's compatibility with the engine, aircraft and airport handling systems, as well as problems associated with blending the additive, storing the additive fuel, and degrading the additive fuel on the aircraft fuel system. A major concern also is cost, not only the cost to produce the additive in large quantities, but the costs associated with quality control, and engine and fuel system modifications.

With regard to future fuels, programs are underway to determine compatibility of the antimist additive with changes in base fuel compositions, such as increased aromatics content, increased boiling point, and decreased flash point. Assessment of various fuels will be accomplished to determine antimisting behavior, cold temperature behavior, rheological behavior, and degradation.

These major problems are being addressed in an extensive engineering and development program underway by the FAA (24) to complete all research necessary to support a notice of proposed rulemaking to be completed by mid 1984 for the introduction of AMK fuel into civil aviation use. Table VI lists the three major phase titles of the FAA program. Phase I is identified as a feasibility and FM-9 development phase and is a continuation of work performed under the US/UK MOU started in June 1978. This phase includes continuation of research on flammability limits, rheology, compatibility, specification and production of AMK, as well as large-scale evaluations of AMK and an economic study to satisfy the concerns identified above.

The second phase of the program is identified as full-scale validations and consists of two main items, ground and flight test of the fuel in an operating system, and the full-scale crash of an aircraft representative of operational use while fueled with AMK.

Phase IIA is an alternate or candidate fuel effort to investigate alternate candidate fuels which can compete with the FM-9 fuel or in case that technical problems arise with the FM-9 fuel that cannot be solved. Success in Phase I and all parts of Phase II on the FM-9 will lead to a mid 1984 data base which would be supportive of a regulatory recommendation to be made by the FAA Technical Center to the regulatory side of FAA. If the data base is very strong, action could be initiated to require use of this fuel for commercial operations. In the event that a definitive statement cannot be made in late 1983, concerning either FM-9 or an alte nate fuel, the intent is to terminate the program.

Fuels Derived From Shale Oil

Oil shale is defined as a fine-grained sedimentary rock containing organic matter which yields oil when heated. Synthetic crude oil and gas are produced from shale oil by a process called retorting which heats the shale rock to a pyrolysis temperature of about 510°C, causing the solid kerogen to decompose to oily vapors and gases, leaving behind a carbonaceous residue of coke on the inorganic fraction of the shale. Retorting can be carried out either in surface facilities or in the ground (in situ).

Oil shale accounts for approximately 5.6 percent of world fossil fuel resources and is found in many countries throughout the world. The largest oil shale reserves are located in the United States and the Soviet Union. The world's largest known deposit, the 16,000 square mile Green River Formation in Colorado, Wyoming and Utah, contains the equivalent of 1.2 trillion barrels of oil.

The only known commercial shale oil industries currently in existence are in China and the Soviet Union. China's shale oil production is very small, in the order of 3000 to 4000 barrels per day, while the current production in the Soviet Union is estimated at 35 to 50 million tons per year. About one-third of the shale retorted in the Soviet Union is used to produce fuel oil and chemicals with the remainder burned directly to furnish energy for electric power generation.

After many years of research and development, an oil shale industry is about to start in the U.S. with commercial plants being designed and construction underway by Union Oil Company and the Colony Project (Tosco and Exxon). Union Oil Company is planning to start production in mid 1983 and under an agreement with the Department of Energy and the Department of Defense will deliver a minimum of 3,000 barrels per day of military aircraft turbine fuel and 7,000 barrels per day of diesel fuel at market price to the Department of Defense for evaluation in their shale-derived fuels evaluation programs. This initial commercial plant will consist of a 12,500 ton per day mine and a Union Oil Company-developed above ground retort which will produce 10,000 barrels per day of raw shale oil. The final step is an upgrading plant that will convert the raw shale oil into a high quality syncrude which will be suitable for normal refinery processing. The Colony Project expects to produce 48,000 barrels per day by 1985. Other planned commercial plants in the U.S. are expected to yield a total of 480,000 barrels per day by 1992.

A substantial advantage of oil shale and tar sands over coals is the more favorable physical and chemical properties, as shown in Table VII. Shale kerogen and tar sands bitumen more closely resemble petroleum crude in hydrogen content, oxygen and sulfur, while nitrogen content is much higher in kerogen. As a result, much less hydrogen is required to remove these constituents from kerogen and bitumen than from coal liquids and to decrease the carbon-hydrogen ratio to the levels required for liquid fuels, such as gasoline, jet fuels, diesel fuels and heating oils. It should also be noted that the carbon-hydrogen ratio of kerogen and bitumen is considerably lower than that of coal, making them much more attractive, both technically and economically, than coals for producing distillate fuels.

Since 1975, several programs have been sponsored by the U.S. Air Force and by private industry to produce aviation turbine fuels from shale oil crude. The major objectives of these programs with Ashland Petroleum Company, Amoco Oil Company, Sun Oil Company, Union Oil Company and UOP Process Division were to define and develop processing technology to economically produce high yields of military jet fuels from shale oil crude. Each company proposed a different approach and processing scheme which are discussed in detail in several reports and papers (25-32). All of the companies have developed satisfactory processing techniques for refining shale syncrude into aviation turbine fuels and other finished products, such as gasoline and diesel fuel. As shown in Tables VIII and IX, the processes yielded JP-4 and JP-8 fuels that meet, and in many cases, exceed current military jet fuel specifications at prices comparable to fuels produced from petroleum crude oil.

Fuels Derived From Coal

Coal reserves are the largest component of the total fossil energy resources, accounting for 75% of all fossil resources worldwide. The most important countries in terms of resources and reserves are the Soviet Union, the United States and China. Australia, Canada, Germany, Poland and the United Kingdom have coal resources in excess of one percent each of the world total.

There are several methods for producing liquid hydrocarbons from coal. These include: (1) hydrogenation, which involves the addition of hydrogen and heat to decrease the carbon/hydrogen ratio of the coal; (2) thermal cracking/pyrolysis, which involves splitting the coal into hydrocarbons, water and carbonaceous residue by heat alone; (3) donor solvents, which involves solvent extraction with a hydrogen-rich solvent, and; (4) gasification/synthesis, which involves gasification of the coal to carbon monoxide (CO), hydrogen (H_2) and methane, followed by catalytic synthesis of the CO and H_2 through the Fischer-Tropsch process to produce hydrocarbons or alcohols.

All countries with major coal reserves have done and are continuing to do small-scale and large-scale development on liquifaction and gasification of various coals. The SASOL plants in South Africa are the only commercial-scale plants producing liquid fuels with most of the liquid fuels used as motor gasoline and the remainder used as chemical feedstock.

In the U.S., two large pilot plants, the H-Coal pilot plant in Catlettsburg, Kentucky and the Exxon Donor Solvent pilot plant in Baytown, Texas are continuing major series of test runs on these liquifaction processes prior to commercialization in the late 80's.

Very limited research and development has been done on the production of jet fuels from coal. In 1976 Exxon Research and Engineering Company, with joint U.S. Air Force and NASA support, evaluated the feasibility of producing jet fuels from synthetic crude oils derived from shale oil and coal (25). Conclusions from this program showed that specification jet fuels can be produced from shale oils by catalytic hydroprocessing of the kerosene fractions, but it is much more difficult to produce such fuels by similar catalytic hydroprocessing of coal liquids fractions. This difficulty with coal liquids results from two factors: (1) the basic chemical composition of coal liquids are high in aromatics and low in paraffins, and (2) typical hydroprocessing catalysts convert some of the aromatics to naphthenes (cycloparaffins) without substantial ring opening or cracking to produce paraffins. As shown in Table X, jet fuels could be prepared from coal-derived liquids, but there would be difficulty in meeting specific gravity and smoke point.

Fuels Derived From Tar Sands

Tar sands are defined as sands containing hydrocarbons so viscous that they cannot be recovered in their natural form by any normal mining methods. It is estimated that world recoverable tar sands total about 2000 billion barrels, with the major deposits in Canada and South America. Because of the similarity of tar sands and heavy oils, these two resources are combined in many resource estimates.

Syncrude from the Canadian tar sands is an important source of energy and Canada is expected to produce more and more synthetic crude from four major formations located in northern Alberta. The best known and largest is the Athabasca tar sands with other deposits known as Wabasca, Peace River and Cold Lake. The potential oil recovery from these deposits are very high with total in-place oil currently estimated at 1350 billion barrels. This is over twice that of total conventional world oil reserves, which have recently been estimated at 640 billion barrels.

In Canada, synthetic crudes from tar sands are being produced by two plants with a combined design capacity of 155,000 barrels per day or about 10 percent of Canadian crude oil production. These plants are expected to expand by the mid 80's to 240,000 barrels per day; by 1990 it is forecast that an additional 320,000 barrel per day capacity will be added, but as with other synthetic fuels projects, the developmental pace is difficult to predict due to economic and political restraints.

Two upgrading plants currently operating in Canada use coking to crack the bitumen to lighter material and to remove heavy metals. The cracked product, which contains considerable olefinic material and has high sulfur and nitrogen levels, is then upgraded further by hydrogenation, producing synthetic crude. Approximately 47 percent of the syncrude is in the middle distillate range which is suitable as refinery feestock for producing jet fuels, diesel fuels and heating oils.

Properties of a Jet A-1 fraction prepared from a tar sands synthetic crude are shown in Table XI and compared to a conventional Jet A-1 from petroleum crude (33). As shown, the most significant property of the tar sands produced Jet A-1 is its very high aromatic content of 32 percent as compared to the average conventional Jet A-1 of 19 percent and the specification limit of 25 percent maximum. This high aromatic content is also reflected in the low hydrogen content and smoke point, as compared to conventional Jet A-1 and specification requirements. On the basis of aromatic content, the amount of tar sands syncrude that can be run at any particular refinery is about 30% of the total crude run with the remainder being petroleum crude. Additional hydrotreating of the Jet A-1 fraction from tar sands syncrude could reduce the aromatics and increase hydrogen content and smoke point to meet Jet A-1 specification requirements, but this increased hydrogenation would depend on hydrogen availability and increased costs of refining.

Other characteristics, including flammability properties, of the tar sands produced Jet A-1 are similar to those of petroleum-derived fuels.

Non-Conventional Fuels

Liquid hydrogen and liquid methane have been recognized by the NATO countries as having potential as alternative aircraft turbine fuels. Fundamental combustion and aircraft design studies have been conducted at various research establishments and airplane companies of the NATO countries. The results of these studies showed that liquid hydrogen or liquid methane offer significant advantages for long range aircraft due to their high gravimetric heating values compared to liquid hydrocarbon fuels. As shown in Table XII, liquid hydrogen has a heating value per unit weight which is approximately three times greater than Jet A. In addition, because their densities are less, the aircraft takeoff gross weight is potentially less using these cryogenic fuels than for liquid hydrocarbon fuels. However, because of their low boiling points and low densities, new aircraft with large insulated tanks must be designed to use these cryogenic fuels. While the very wide flammability limits are desirable as turbine engine fuels, they are less attractive from the viewpoint of aircraft safety. In addition, the storage and support systems required at airports would be complex and expensive compared to those for liquid hydrocarbon fuels. The logistic problems of supplying these fuels to remote areas throughout the world appear formidable. The projected cost of producing these fuels appears appreciably higher than for liquid hydrocarbons. Therefore, until inexpensive means of production are developed, these cryogenic fuels will not be seriously considered as fuels for aircraft applications.

CONCLUDING REMARKS

Current aviation turbine fuels produced from petroleum pose a definite fire and explosion threat regardless of their volatility characteristics. Based on laboratory tests and crash analyses, however, kerosene-type aviation turbine fuels appear to be safer than wide-cut fuels under most conditions during ground handling and use in the aircraft. In view of these safety advantages, most airlines and military air forces favor the use of kerosene-type fuels, but due to availability and cost problems, have not totally converted.

Projected changes in fuel properties of current fuels (aromatics, freezing point and final boiling points) which will lead to increased availability and greater flexibility in supply at possibly lower prices will have very little impact, if any, on the fire properties of such fuels. The only exception to this is a reduction of flash point of kerosene-type fuels from the present 38°C to 32°C which might adversely impact the fire and explosion threat of these fuels.

Reductions in misting characteristics of kerosene-type fuels through the use of the antimisting additive approach shows promise of significant fire protection in post-crash situations where a fireball could exist. Many technical problems are now being addressed, and if successful, it is possible that the introduction of such additive fuels would be used in civil aviation in the 1984 time period.

Acceptable aviation turbine fuels can be produced from shale oil, coal and tar sands. Properties of these fuels are expected to be similar to those produced from petroleum with respect to fire properties. Due to the difficulty and cost of producing jet fuels fro coal, it is expected that coal liquids will be used as r-finery feedstock for producing motor gasoline and heating oils.

The cryogenic liquids, hydrogen and methane, offer little potential as aircraft fuels, at least until other sources of liquid hydrocarbon fuels are exhausted. The fire hazards involved with these cryogenic fuels during ground handling and in the aircraft are sufficiently different than with present liquid hydrocarbon fuels and would require special design of both ground handling systems and aircraft.

Aircraft in the inventory today, as well as those under development, both military and commercial, are designed to use liquid hydrocarbon fuels of the types now being used, and as a result, future fuels will be very similar in fire properties to those used today.

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TABLE I

Typical Volatility Characteristics of Aviation Turbine Fuels

Property	JP-4 Jet B	Jet A/A-1 JP-8	JP-5
Reid Vapor Pressure, kPa @ 38°C	18	1.4	1.6
Distillation, °C			
Initial Boiling Point	61	167	182
End Point	239	266	258
Flash Point, °C	-29	46	62

TABLE II

Typical Flammability and Ignition Properties of Aviation Fuels at One Atmosphere

Property	JP-4 Jet B	Jet A/A-1 JP-8	JP-5
Net Heat of Combustion			
kJ/kg	43,570	43,240	43,050
MJ/m^3	33,190	35,060	35,200
Limits of Flammability, % by Vol			
Lower	1.3	0.6	0.6
Upper	8.0	4.7	4.6
Flammability Temperature Limits, °C			
Lower (Lean) Limit	-23	53	64
Upper (Rich) Limit	18	77	102
Minimum Electrical Spark Ignition Energy, mJ	0.20	0.20	0.20
Autoignition Temperature, °C	246	238	241
Flame Spread Rate, Quiescent Liquid			
m/Min @ 27°C	~225	~7.5	~7.5

TABLE III

Air Force Future Fuel Specifications

	Future JP-8	Present JP-8	Future JP-4	Present JP-4
Final Boiling, °C, max	316	300	288	270
Flash Point, °C, min	32-54	38	---	---
Freeze Point, °C, max	-34	-50	-50	-58
Net Heat of Comb, Btu/lb, min	18,300	18,400	18,300	18,400
Aromatics, Vol%, max	35	25	35	25
Hydrogen, Wt%, min	13.0	13.5	13.0	13.6
Nitrogen, Wt%, min	0.005	---	0.005	---

TABLE IV

Major Projected Changes In Fuel Properties - NASA

Property	Future Broad-Spec Fuel	Current Jet A
Aromatics, Vol%	30-35	25 max
Hydrogen, Wt%	12.5-13.0	13.5-14
Final Boiling Pt, °C	290-330	280 max
Freezing Point, °C	-29 to -34	-40 max
Thermal Stability		
(JFTOT Breakpoint), °C	$\geq$240	$\geq$260

TABLE V

Major Problems/Concerns
Associated With Antimisting Kerosene

- Fuel Compatibility
  - Engine
  - Aircraft
  - Airport Fuel Handling System
  - Future Fuels
- Additive Blending Procedures
- Additive Fuel Storage
- Additive Fuel Degradation Procedures
- Additive Fuel Costs

TABLE VI

Antimisting Fuel Program Phases

Phase I - Feasibility/FM-9 Development

Phase II - Full-Scale Validation

- Ground Tests
- Flight Tests
- Crash Tests

Phase IIA - Candidate Fuels Evaluation

TABLE VII

Properties of Synthetic Crude Sources

	Shale Kerogen	Athabasca Bitumen	Bituminous Coal	Lignite	Petroleum Crude
Carbon, Wt%	80.5	81.1	78.8	72.5	86.0
Hydrogen, Wt%	10.3	10.4	5.7	4.9	13.6
Oxygen, Wt%	5.8	4.1	8.9	20.8	0.1
Nitrogen, Wt%	2.4	0.6	1.4	1.1	0.1
Sulfur, Wt%	1.0	3.8	5.2	0.7	0.2
C/H Ratio	7.8	7.8	13.8	14.8	6.3

TABLE VIII

JP-4 Fuels From Shale Oil Crude

	UOP	Ashland	Sun Tech	Union	MIL-T-5624L
Density, kg/m^3	781	782	776	775	751 - 802
Distillation Temperature, ^{o}C					
Initial	95	----	70	60	Report
10%	124	----	----	121	----
20%	142	116	127	142	145 max
50%	197	151	172	178	190 max
90%	248	226	237	219	245 max
E.P.	269	258	275	241	270 max
Freeze Point, ^{o}C	<-58	-68	-58	-51	-58 max
Smoke Point, mm	28.5	----	----	37	20 min
Vapor Pressure, 38^{o}C, kPa	5.5	20	18	18	14 - 21
Viscosity @ -20^{o}C, cSt	3.21	----	----	----	----
Copper Strip Corrosion	1A	1B	1A	1A	1B max
Total Sulfur, Wt%	0.07	nil	0.0003	nil	0.40 max
Mercaptan Sulfur, Wt%	0.0001	nil	0.0001	<0.00003	0.001 max
Hydrogen, Wt%	14.39	14.14	14.16	14.35	13.6 max
Aromatics, Vol%	8.7	11.0	15.0	8.0	25 max
Olefins, Vol%	nil	nil	1.0	nil	5 max
Combustion, MJ/kg	47.2	43.3	43.5	----	42.8 min
Thermal Stability					
Pressure Drop, mmHg	1.5	0	0	0	25 max
Tube Deposit	0	0	0	0	3 max

TABLE IX

JP-8 Fuels From Shale Oil Crude

	UOP	Ashland	Sun Tech	MIL-T-83133 SPEC
Density, kg/m^3	797	819	811	775 - 840
Distillation Temperature, ^oC				
Initial	142	----	99	Report
10%	161	176	154	205 max
20%	178	----	178	----
50%	223	----	210	----
90%	267	----	266	----
E.P.	289	286	293	300 max
Freeze Point, ^oC	-48	-52	-57	-50 max
Flash Point, ^oC	38	46	38	38 min
Smoke Point, mm	27.2	----	----	20 min
Viscosity @ -20^{o}C, cSt	5.67	----	----	8.0 max
Copper Strip Corrosion	1A	1B	1B	1B max
Total Sulfur, Wt%	0.05	nil	0.0003	0.40 max
Mercaptan Sulfur, Wt%	0.0005	0.0005	0.0002	0.001 max
Hydrogen, Wt%	14.1	13.83	13.85	13.5 min
Aromatics, Vol%	9.3	19.3	16.0	25.0 max
Olefins, Vol%	nil	nil	2.0	5.0 max
Combustion, MJ/kg	46.2	43.0	43.2	42.8 min
Thermal Stability				
Pressure Drop, mmHg	0	0	0	25 max
Tube Deposit	0	0	0	3 max

TABLE X

Aviation Turbine Fuels From H-Coal Liquid

	JP-4	JP-4 Spec	Jet A	Jet A Spec
Density, kg/m^3	806	751-802	846	775-840
Distillation, ^oC				
Initial	88	Report	171	Report
10%	108	----	187	204 max
20%	118	145 max	194	----
50%	152	190 max	210	232 max
90%	193	245 max	234	----
E.P.	219	270 max	247	288 max
Freeze Point, ^oC	<-70	-58 max	-44	-40 max
Smoke Point, mm	22	20 min	18	19 min
Viscosity @ -34.4^{o}C, cSt	3.07	----	9.35	15 max
Total Sulfur, Wt%	0.001	0.40 max	0.002	0.3 max
Hydrogen, Wt%	14.29	13.6 min	12.66	----
Aromatics, Vol%	16.5	25 max	18.5	25 max
Olefins	0.9	5 max	0.8	----
Flash Point, ^oC	----	----	57	38 min

TABLE XI

Properties of Jet A-1 From Tar Sands Syncrude

	Tar Sands	Petroleum	Jet A-1 Specification
Density, kg/m^3	830	803	840 max
Viscosity, cSt at 40^oC	1.3	1.2	----
Freeze Point, ^oC	<-60	-50	-47 max
Sulfur, ppm	38	100	3000 max
Nitrogen, ppm	4	2	----
Hydrogen, Wt%	12.9	13.9	----
Aromatics, Vol%	32	19	25 max
Naphthalenes, Wt%	0.6	2.2	3 max
Smoke Point, mm	13	22	20 min

TABLE XII

Physical Properties of Non-Conventional Fuels

Property	Liquid Hydrogen	Liquid Methane	Jet A-1
Boiling Point, ^oC	-253	-162	167
Liquid Density, kg/m^3	71 @ -253^oC	422	827
Heat of Combustion			
MJ/kg	120	50	42.8
MJ/m^3	8,520	21,100	35,400
Flash Point, ^oC	---	---	38 min
Autoignition Temp, ^oC	585	537	238
Limits of Flammability, % by Vol			
Lower	4.0	5	0.6
Upper	75	14	4.7

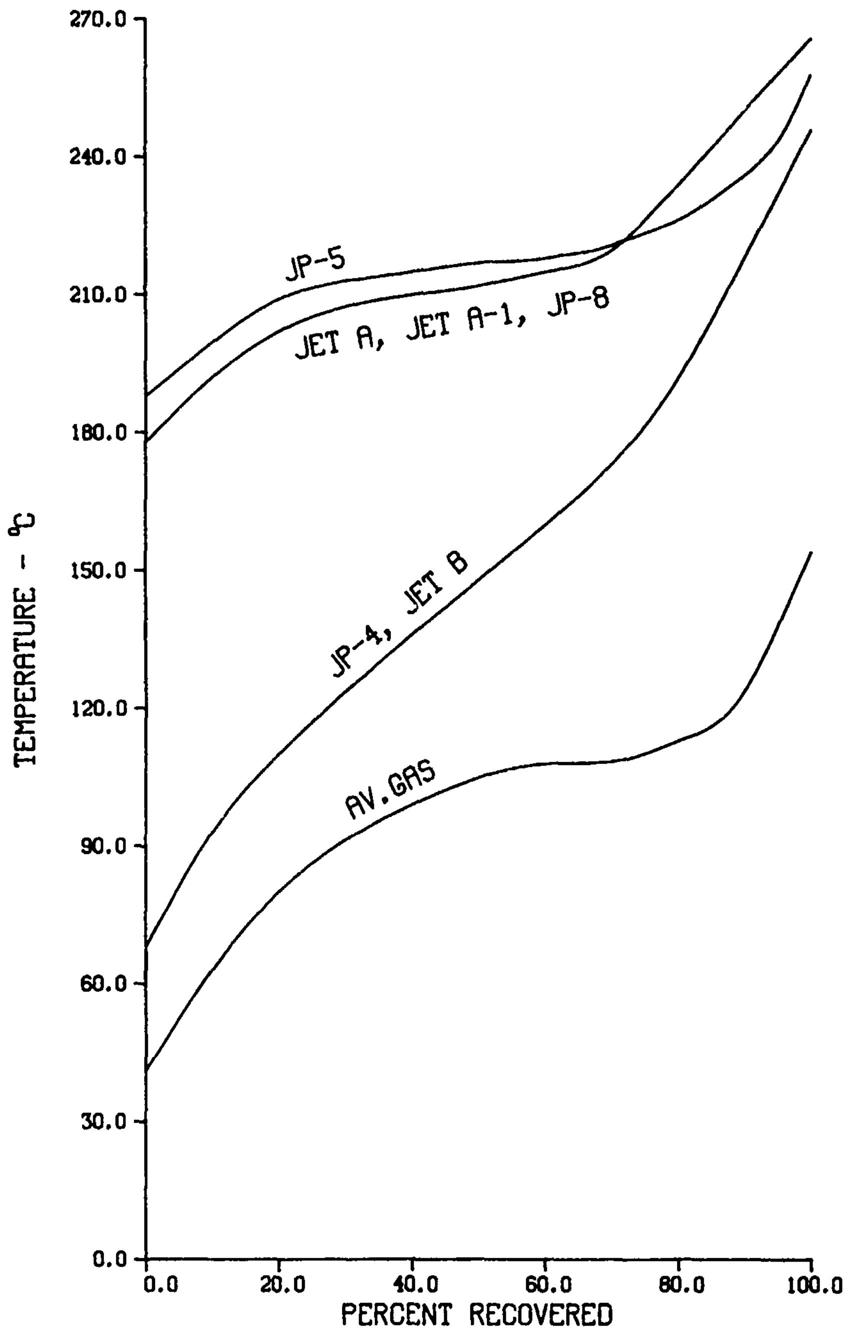

Figure 1. Typical Distillation Curves

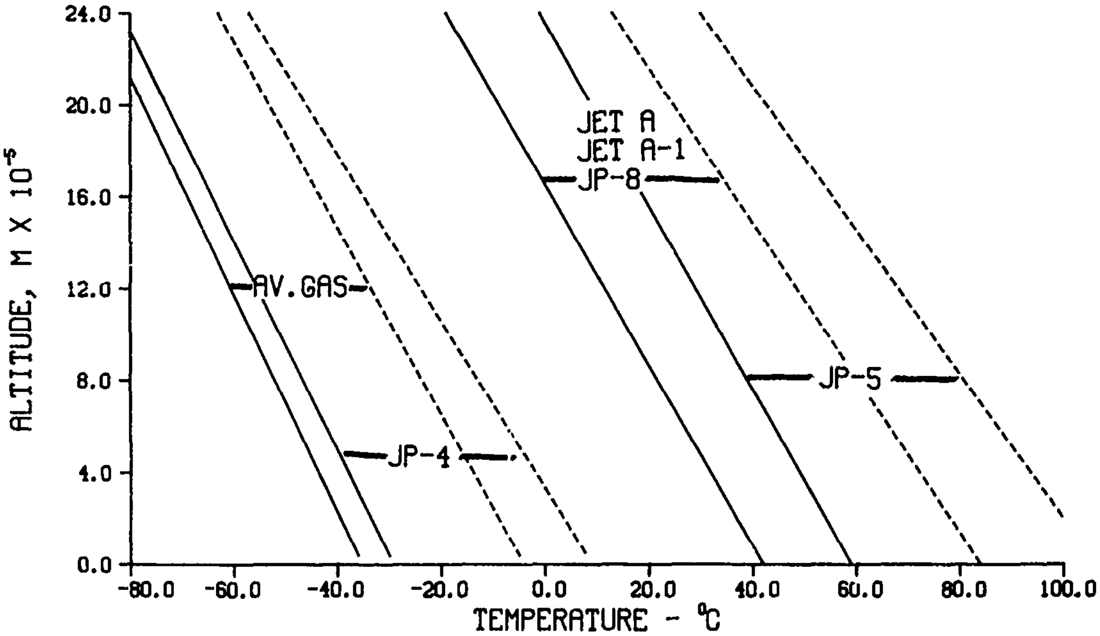

Figure 2. Fuels Flammability Limits Vs Altitude

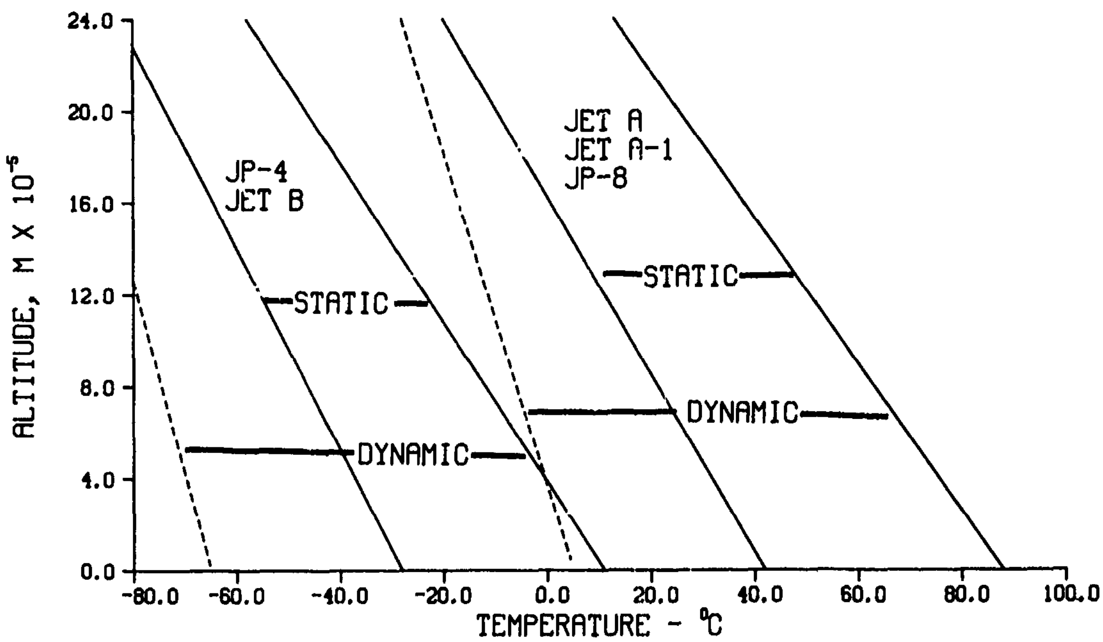

Figure 3. Effects of Dynamics on Flammability Limits

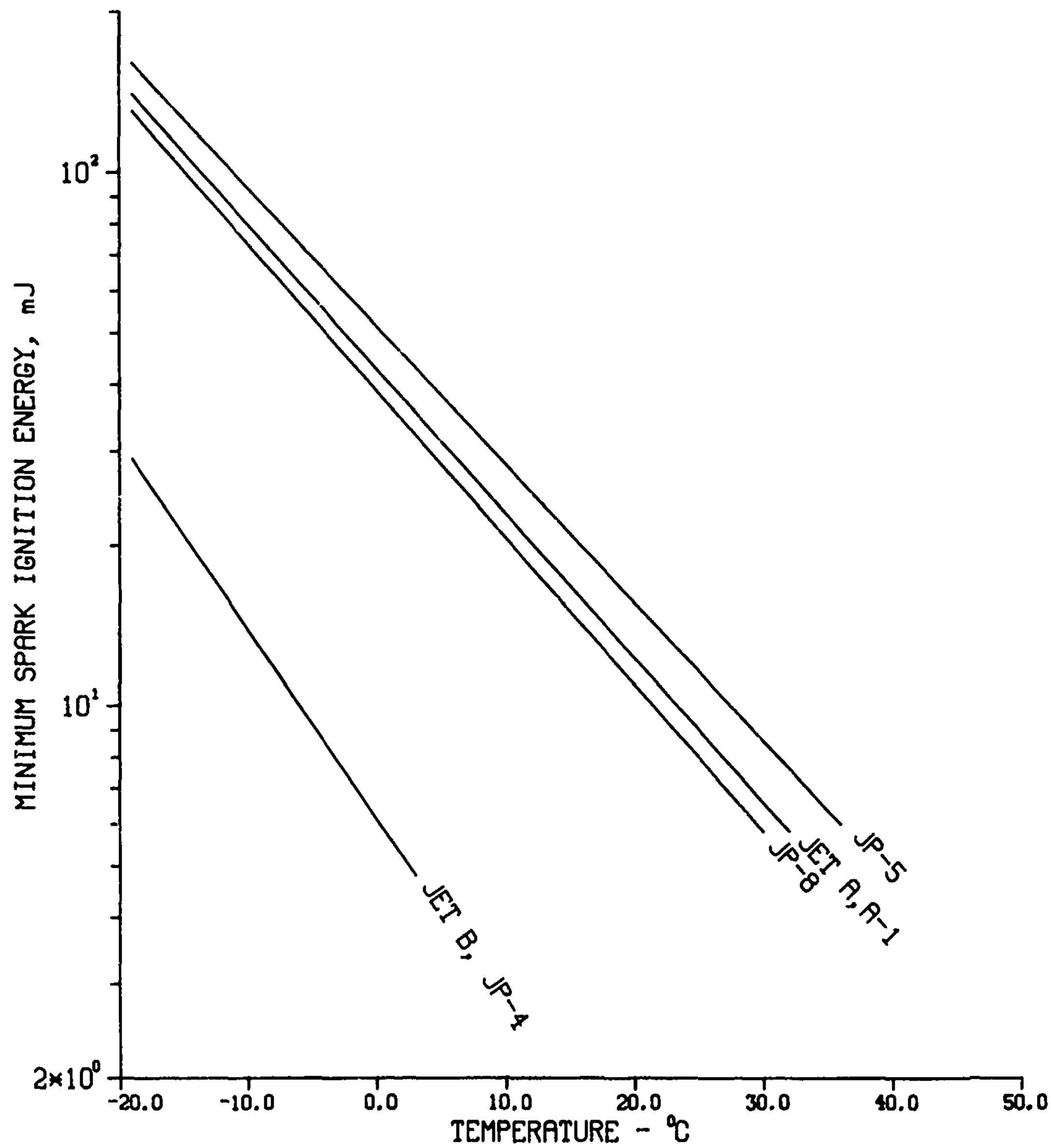

Figure 4. Minimum Spark Ignition Energy for Aircraft Fuel Sprays

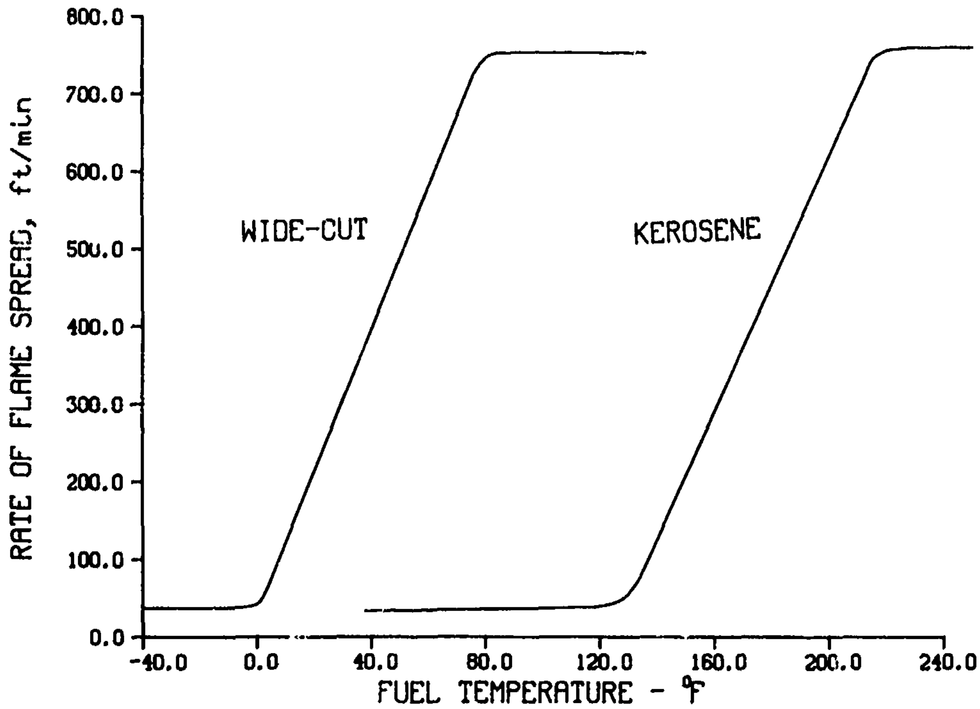

Figure 5. Flame Spread Rate of Fuels

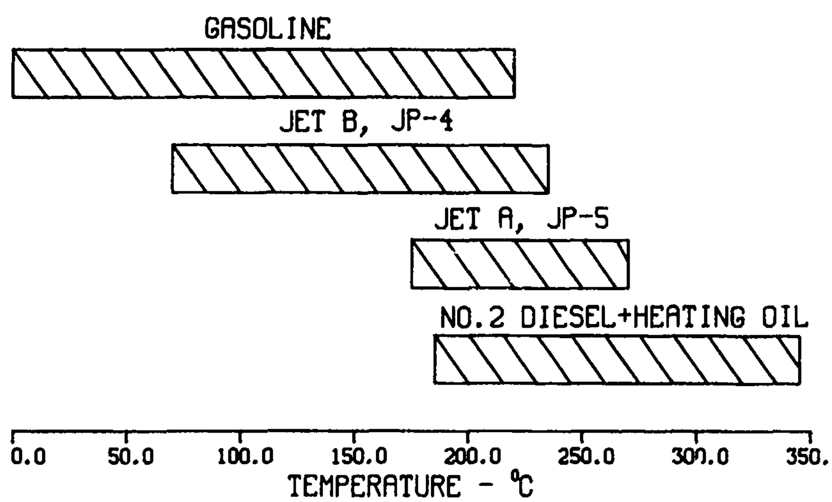

Figure 6. Boiling Range of Various Fuels

FUEL SYSTEM PROTECTION METHODS

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SUMMARY

Fuel system protection equipment is being researched and developed for military aircraft and helicopters to reduce the major cause of aircraft loss which is attributed to fires and explosions occurring under combat conditions.

Arising largely from these investigations a wide range of equipments is now available for fitment to civil transport for survivability enhancement provided that the associated weight and operational penalties can be accepted.

Aircraft fire safety and crash resistance should be considered in the initial design concept and the appropriate safety precautions taken to minimise the risk of fire and explosion both inflight and on the ground. Caution should be exercised in the introduction of composite structures and new fuels.

Introduction of fuel containment systems and anti-misting fuels could be the key factors in reducing dynamic fuel spillage and improving occupant survivability in the case of the post crash fire.

1 INTRODUCTION

In a modern combat aircraft or helicopter the fuel occupies a large proportion of the total volume and is a source of potential energy, which may be employed by an enemy to bring about the destruction of a military aircraft.

The fuel system (tankage and associated pipe systems) is the largest single vulnerable component (apart from the structure) and forms a very significant target even in small aircraft. Fuel fires and tank explosions together with their associated effects account for more than 60% of all combat losses.

Fuel system protection methods have, therefore, been devised to minimise the risk of fire and explosion and reduce fuel loss due to battle damage. Some of these methods can be applied to civil transports for the enhancement of inflight and post crash survivability, in an endeavour to reduce the number of fatalities due to fire and explosion.

2 FUEL CONTAINMENT

2.1 Crashworthy fuel systems

Energy absorbing structures and crashworthy fuel systems are currently being introduced into new helicopters to improve fuel containment and thereby minimise the quantity of spilt flammables flowing into areas in which ignition sources may be present during ground impact.

The basic aim is for the fuel system to remain leak tight with vertical impact drop tests made onto a non-deformable surface with the tankage structures maintained in a horizontal plane.

Special attention is devoted to the flexible fuel tank bladder construction, in particular its ability to conform to the desired shape at impact, its resistance to mechanical intrusions and the integrity of the various pipes and connectors.

Fuel pipes are run, preferably, within fuel tankage and at reduced pressure using suction pumps wherever possible; pipes are provided with a high degree of flexibility, resistant to cutting and fitted with break-away self-sealing valves. Vent pipes are also fitted with check or anti-spill valves and flexible connectors to minimise spillage at toppling and impact.

Fuel pumps and fuel capacitance probes are provided with frangible retainers and weak points to minimise the risk of bladder separation and component penetration of tank walls.

Electrical cables are run over fuel tanks and along structural members and provided with sufficient slack to allow for structural deformation.

2.2 Self-sealing fuel tanks and pipes

Self-sealing crash resistant flexible bladder fuel tanks are also being introduced into a wide range of fixed and rotary wing military aircraft.

Self-sealing fuel tanks, together with their associated anti-petalling or backing boards, are used to seal up perforations caused by a wide range of combat threats, including ball and armour piercing projectiles, as well as fragments from shells and missiles.

With the current natural and synthetic sponge and sheet rubbers employed in the tank and pipe fabrication, the desired swelling and closure of the tank or pipe wound on contact with fuel normally occurs within a few minutes; this is dependent on the tank or pipe pressurisation, aromatic content and temperature of the fuel.

Attempts have also been made to reduce the time taken to seal the wound by plugging with either a fuel gelling or a plastics foaming agent incorporated within the fuel tank wall; covers with improved resistance to tear and with built in energy absorption are also being investigated.

2.3 Compartmented tank construction

An alternative approach to self-sealing in military aircraft, is to use simple compartmentation of the fuel tankage for both fuselage and wing fuel tank locations.

A novel compartmentation technique currently under evaluation at RAE is based on packing the interior of the tank with vertical shaped columns of reticulated foam, each of the small columns being individually wrapped in a thin plastics envelope and fitted with a non-return valve feeding into a manifold distribution system. The entire tank is provided with an explosion suppressant intank filler and the proposed construction is aimed at providing fuel containment, explosion protection and hydraulic shock alleviation. (Figs 1 and 2.)

3 EXPLOSIONS AND FIRES

In military combat aircraft fuel fires initiated in bays or voids adjacent to the fuel tankage[1] are the greatest risk in terms of frequency of occurrence but a fuel tank internal explosion[2] can have immediate and serious consequences to both aircraft and crew.

3.1 Explosions

The ullage or space above the liquid fuel in an aircraft tank contains a mixture of fuel vapour or fuel mist and air which can be ignited by a spark, flame or hot surface, provided that the mixture is within certain limits.

The conditions required for ignition and subsequent flame propagation through the mixture are dependent on a number of parameters including fuel type, fuel temperature, tank pressure and oxygen concentration.

In flight, fuel froths and fuel mists are generated by the aircraft vibration and oxygen rich 'air' is released from the supersaturated fuels at reduced pressure conditions.

There are times in the life of a military aircraft or helicopter, both on the ground and in flight, when the fuel tank ullage is potentially at risk to ignition.

If a high velocity projectile penetrates the skin of an integral fuel tank, ignition sources are immediately provided by the impact flash in the form of hot incandescent particles, also additional incendiary products may be released into the ullage (Fig 3).

3.2 Fires

With the current constructional techniques used to house the aircraft internal fuel containment systems there are numerous voids or bays formed between the tankage and aircraft skins in which primary fuel fires can be readily initiated and sustained.

If a high velocity projectile penetrates the outer aircraft skin, ignition sources are immediately provided by the impact flash and the release of incendiary products. These are able to ignite the finely atomised fuel spray which is ejected with considerable force in discrete pulses from the punctured fuel tank as the projectile decelerates within the fuel (Fig 4).

The passage of the projectile through the void and into the fuel provides ideal conditions for establishing a sustained fire external to the tank but within the cloistered atmosphere provided by the aircraft structure.

Secondary fires may also occur due to fuel, hydraulic fluid and/or engine lubricating oil released from ruptured tanks or pipes coming into contact with spark and/or spontaneous ignition sources other than those provided by the threat.

In the case of a crash, spilt fuel together with enveloping fuel mist from ruptured tankage and pipes can lead to a post crash fire, the fuel being ignited by hot engine components, friction sparks, severed electrical wiring etc.

An explosion within a fuel tank can also lead to a fire within the surrounding structure or, in the case of a crash, it can significantly add to the damaging effect of a post crash fire.

4 PROTECTION SYSTEMS

4.1 Explosion protection

Various systems may be used to suppress fuel tank and vent pipe explosions in military aircraft.

These systems are essentially based on (a) reducing the oxygen content of the ullage below the critical value necessary for ignition by the application of inert gases including nitrogen, carbon dioxide and combustor gas products or (b) suppression of the propagating flame and incipient explosion by using flame arresters and fire extinguishants.

The currently preferred system for the fuel tankage of the larger transport aircraft is based on nitrogen inerting of the ullage to maintain an oxygen concentration below 9% by volume, using either a liquid/gaseous storage or an onboard oxygen/nitrogen separation unit. T se units are essentially based on semi-permeable hollow fibres and membranes together 'th molecular sieves using pressure swing adsorption. For the smaller aircraft and helicopters intank fillers based on reticulated plastics foams, melded polyamide fibrous structures or expanded metallic foils are a more attractive solution (Fig 5). Fuel system engineering assessments of melded polyamides intank fillers are being carried out by RAE (Fig 6).

An alternative approach is to suppress the propagating flame with an extinguishant immediately following ignition (within 20 ms) and prior to a large pressure rise being developed, the initial rapid rise of pressure or the light emitted at ignition being used to trigger the rapid discharge of extinguishant. With a single shot system, once operated, it ceases to be effective when the concentration of inerting fluid has decayed.

A comparison of explosion protection system weights for fuel tankage is given in Table 1.

Flame arresters and extinguishants are also being used to inhibit flame propagation within vent pipe systems; however, care must be exercised to ensure that flame arresters (gauzes and foams) do not become (a) blocked by ice or debris and cause an undue pressure difference within the vent system and (b) subjected to high temperatures with subsequent loss of suppression effectiveness.

4.2 Fire and smoke detection

Thermally sensitive continuous loops and point detectors are widely used to detect both fire and overheat conditions arising within power plant installations and voids adjacent to fuel tanks.

These detectors sense changes in electrical conductivity or pressure or the outputs of differential thermocouples. However, thermal sensing systems are not recommended for protection of voids against combat fires due to their relatively long detection delays (0.5 second to 10 seconds).

Studies have shown[1] that severe fires can develop in 4-5 seconds and that the optimum time to extinguish a combat fire is within a few milliseconds (1-5 ms) of its initiation.

Overheat detectors are used to monitor hot air leaks from ducting and optical surveillance sensors are used to detect engine light up (in particular reheat), combustion chamber flame break out and flame propagation within fuel vent pipes.

Sensors based on detecting both ultra-violet and infra-red radiations emitted from flames are now being actively developed for use in combat fire protection systems. These detectors can be made to respond to impact flash, incendiary products and hydrocarbon fires; they offer rapid response to fire (1-2 ms) and are designed to have a low probability of producing a false warning for a wide range of stimuli (Fig 7).

The atmosphere of compartments such as electronics bays and baggage holds can also be inspected for the presence of both smoke and flammables using visual, ionisation and photocell detectors with associated built in sampling systems (Fig 8). Dilution of high concentrations of contaminants may be afforded by re-directing the cabin air conditioning discharge[3]. Cockpits should preferably be maintained at positive pressures relative to the cabin to delay smoke migration onto the flight deck.

4.3 Fire suppression

4.3.1 Active dispersal systems

Optical fire detector outputs are currently used to activate small detonators which in turn disrupt the diaphragms of either pressurised bottles containing vapourised extinguishants (halons) or dry powder suppressors (Fig 9).

The selection of an extinguishant depends upon the threat and compartment configuration. Powder extinguishants have excellent fire 'knock down' and flame inhibiting qualities in smaller voids, while vapour extinguishants offer good penetration and suppression in larger spaces and persist longer, particularly where ventilation is of a low order. For heavily congested voids vapour extinguishants are preferred.

Extinguishants are normally released within 5 ms of the projectile strike and primary fires suppressed within a further 10-20 ms. Rapid response systems provide inerting concentrations prior to the fire gaining a firm hold and compartment break up due to internal shell burst, thereby minimising the quantity of extinguishant necessary for suppression.

4.3.2 Passive suppression systems

Various plastics foams and fibrous structures have been placed between aircraft skin and fuel tank surface to minimise the risk of fuel fires in the associated voids under combat conditions. Low and high density, flexible and semi-rigid, reticulated, open and closed pore structures have been investigated. The preferred non-load bearing void fillers are based on a three-dimensional fibrous structure of melded polyester and a reticulated polyether.

Firing trials have shown various materials to be effective against both inert and incendiary projectiles provided they completely fill the space, *ie* intimate material contact between filler and bay walls.

Plastics foams and fibrous structures are particularly suited to the narrow uncongested voids often found between fuel tanks and aircraft skins.

'In situ' foam filling of voids during build or as an emergency fit has also been considered. This method has been shown to be feasible provided that the surfaces are free of contamination and the voids contain no control runs or other moving parts.

Pressurised inert gases or extinguishant vapours (*eg* halogenated hydrocarbons) can also be contained in lightweight packs located against the fuel tank wall, the contents being released by the projectile penetration.

Various pack designs have been investigated based on (a) drop stitch rubberised or plastics bags (b) reticulated plastics foam bonded onto a plastics bag and (c) interconnected honeycomb bonded to a plastics or metallic cover.

Fire extinguishant powders can also be contained in thin lightweight packs, the selected powder being hermetically sealed within the pack, which is designed to provide the desired shape for maintaining intimate contact with the fuel tank wall. Packs consist of a thin small cell honeycomb or flexible reticulated core with a plastics or metallic film covering. Honeycomb panel dry bay structure can also be powder filled to provide protection.

Powder packs are less bulky than the vapour packs and the finely divided powder is ejected from the pack by the direct shock produced by the projectile/shell together with any associated hydraulic shock arising from the fuel tank penetration.

The choice of system is dependent on many factors, particularly its effectiveness against the threat, also on system weight, complexity, reliability and maintainability. Dry bay volumes and congestion are important considerations, see Table 2.

5 CRASH SWITCHES AND TRIPS

Unidirectional, inertia operated crash switches are used on military fighter and transport aircraft for improving survival under crash conditions. These switches are designed for horizontal mounting and operate when subjected to a forward deceleration equal to or greater than their selected 'g' setting. An alternative form of crash switch may be mounted at strategic positions on the under-surface of the aircraft, contact with the ground operating a lever mechanism for switching purposes.

Crash trips are also employed in which physical deflection at some strategic point of the aircraft structure will deform steel strips embodied in a flexible rubber tube and provide the desired switching.

The operation of crash switches and trips can be used to isolate electrical supplies and/or flammables and to activate directly emergency systems including fire and explosion suppression equipment used in power plants, fuel tanks and associated dry bays.

6 POWER PLANT INSTALLATION

In designing the power plant installation for both military and civil aircraft, careful consideration is given to minimising the hazards resulting from the non-containment of engine debris, combustion chamber flame break out, titanium and fuel fires. With engine break up there is also the risk of fuel fires in voids or intank explosions due to debris penetration and efforts are made to optimise the engine positioning and to locate sensitive components and circuits in safe areas. Vital parts of the engine/fuel system may be protected by armour.

On the question of combustor chamber flame break out endeavours are made to prevent the torching flame penetrating critical components such as the fire wall or structural members. In order to provide a suitable fire barrier, capable of withstanding the severe torching flames (1700°C) dense, expensive and costly materials such as tantalum, zirconium ceramic stainless steel coatings and mineral wool sandwiches are used as both heat shields and deflectors.

Torching flames are difficult to detect due to their localised form (typically 25 mm diameter), however, thermally sensitive loop systems and optical surveillance fire detectors are used for this purpose.

Titanium fires can also occur due to engine break up and blade rubbing in the presence of high pressure airflows; temperatures rising to 3000°C for up to 20 seconds. With the use of titanium alloys on the increase, certain engine design precautions are now being taken, in particular it has been found that the use of titanium for both rotor and stator blades can lead to problems (titanium/titanium rubbing) and the preferred use of titanium is for rotating parts only. Protective materials (coatings) are also being investigated, these should withstand the effect of molten debris and hot gases issuing from a titanium fire.

The power plant installation is also designed and operated to maximise the effectiveness of the existing fire extinguishing systems in that ventilation airflows are kept low, zones are compartmentalised, fuel isolation valves fitted and blow-off panels and drainage holes provided.

Engine and auxiliary power unit fire detection and suppression equipments are normally considered satisfactory except when engine break up is not contained or a titanium fire occurs, in the latter case fire proofing is normally used to contain the fire and prevent its spreading to the airframe and fuel system.

7 FUTURE AIRCRAFT STRUCTURE AND SYSTEM DESIGNS

7.1 Aircraft structure and fire hardening

Increasing interest is being shown in the introduction of various composites into both military and civil fixed and rotary wing aircraft designs with a view to saving on weight, improving performance and economising on fuel.

The military interest is mainly centred in providing composite structures for wing and wing box, fuselage panels, control rods and control surfaces, rotors and tail booms and the civil interest in fairings, access panels, undercarriage doors, control surfaces, shrouds and cabin floors.

Introduction of various composites into both primary and secondary structure is already taking place and weight savings of up to 20% are forecasted. Incorporation of composites into the aircraft structure may improve fire safety in that debris penetration will be accompanied by minimum sparking and improved thermal insulation provided for fuselage fire hardening; however, extreme care must be exercised to minimise structure break up on impact in order to limit fuel spillage and retain passenger compartment integrity.

Exposure of the composites to flame may well result in additional combustion by-products and further work may be required to assess these effects.

The maintenance of cabin integrity is of prime importance and consideration is being given to fire hardening of metallic fuselage structure and transparencies to withstand an external fire and minimise the risk of burn through.

Surface protection of the fuselage and tankage by the application of thermal insulation including phenolic coatings, intumescent paints and foams is considered to be feasible; cabin transparencies with improved fire resistance and structure integrity over thermoformed acrylics, polycarbonates and glass are being sought and polyether sulphones and transparent epoxy compounds capable of forming a hard tough surface char are being investigated. Thin internally mounted metallic covers may also be used for shielding transparencies.

There is the possibility of on-board water supplies (utility services) being ducted to cool transparencies, escape shutes and fuselage surroundings in critical areas, or mixed with a fire fighting foam to clear a path through the external fire for occupant evacuation, provided sufficient water can be available at the time of the post crash fire.

Improved structural volume efficiencies are being sought within both wing and fuselage for the carriage of fuel/passengers and the installation of systems. Ease of access is an important factor for serviceability but it is stressed that every attempt must be made to segregate flammables and ignition sources.

Attention should also be given to designing the wing fuel tankage in a manner such that wing separation or undercarriage collapse on impact will provide minimum fuel spillage.

7.2 Fuel and fuel systems

Modification of current jet fuel specifications to ensure adequate future availability of aircraft hydrocarbon fuels could well result in changes in aromatic content, freeze point and volatility. Higher freeze points can necessitate bulk fuel heating with increased volatility, this together with a lowering of flash point will increase the fire risk.

Turning from hydrocarbons, a likely successor under consideration (despite its low density and low temperature) is liquid hydrogen in that it is attractive from a calorific viewpoint. However, in view of its high volatility, wide flammability range and high rate of flame propagation concern has been expressed as to safety associated with the storage and handling of hydrogen both on the ground and in flight.

It is envisaged that the large and well insulated fuel tanks will dictate the overall aircraft design. Venting of the cryogenic liquid from the fuel tankage would occur under both ground and flight conditions and efflux must be kept clear of all ignition sources. Clearance of electrical equipment for operation within both fuel tank and associated dry bays will demand more stringent testing than that used for hydrocarbons.

Liquid hydrogen spillage from disrupted aircraft tankage and pipe systems could present a serious fire hazard.

Turning to anti-misting kerosines based on low volatility hydrocarbons, a Memorandum of Understanding between the USA and UK was set up in 1978 and this has led to a joint programme based on laboratory and fullscale validation of FM9 fuel.

Engineering problems still exist with regard to degradation of the fuel, blending and filtration. However, problems with fine filters can be avoided if fuel is sufficiently degraded. Some degradation is essential from the point of view of heat exchangers and certain fuel system components.

The potential benefits of anti-misting fuels (FM9 and its derivatives) are considered to be high since the risk of a sustained fire occurring on aircraft impact are extremely low provided that the fuel temperature is below the flash point.

The use of anti-misting fuels in current and projected aircraft is considered technically feasible but cost effectiveness studies have yet to be undertaken.

7.3 Hydraulic fluids and hydraulic systems

Attempts are being made to produce new hydraulic fluids having low flammabilities with a view to further reducing the fire risk from both spark and spontaneous ignition sources.

In order to reduce system weight and volume, studies are being made on the implications of introducing higher system operating pressures (20-55 MPa). The introduction of higher pressures will increase the leakage rate and provide improved atomisation of the fluid released from damaged system components and piping; this will increase the fire risk.

8 PROTECTIVE MEASURES, PENALTIES AND EFFECTIVENESS

Turning briefly to the various protective measures outlined in the previous sections, crashworthy fuel systems are being fitted to both military and civil helicopters and light aircraft and their use could possibly be extended to cover larger transport aircraft.

Separate fuel system components are available for retrofitting into existing fuel systems, including self-sealing breakaway connectors and pipes. Tank compartmentation, tank location and fuel management procedures including jettisoning can be arranged to minimise fuel spillage in the event of an impact.

The crashworthy fuel system is essentially dependent on the use of flexible bladder type tanks (as opposed to integral wing tank construction normally employed in the large civil aircraft), thereby imposing a high fuel volume loss (up to 20%) and a severe weight penalty (up to 6% of the aircraft weight). Containment of fuel in selected vulnerable tankage would reduce these penalties.

In the event of a tank or pipe rupture anti-misting kerosine would reduce the risk of fire and investigations are continuing on both the chemical and engineering problems associated with the use of the specialised fuel. It is now considered to be technically feasible to employ these fuels in both current and projected aircraft. Anti-static fuel additives may be used to increase the conductivity of fuel and special bonding techniques employed with carbon composite constructions to increase surface charge dissipation and minimise the risk of electrical discharges within fuel tankage.

Explosion protection systems are being fitted to military aircraft covering fuel tankage and vent pipes. However, nitrogen fuel tank inerting (other than on-board separation units) does incur logistics penalties and intank fillers impose a loss of fuel volume and a subsequent range penalty.

Fire suppression systems can be adapted for civil transport applications and extended to cover areas other than the power plant such as fuel tank dry bays, freight holds and associated vulnerable regions; but it is stressed that the limited weight of extinguishant carried in flight will have little effect on suppressing the post crash external fire once it has gained a hold.

Fire hardening of the fuselage structure in critical areas such as emergency exits is feasible (with its attendant weight penalty) and improved fire resistance of transparencies is possible.

However, when the fuselage is ruptured or apertures opened up, the products of the external fire combustion become a serious problem with regard to passenger survivability.

The fitment of fuel system protection systems will undoubtedly enhance occupant survivability by reducing the risks of fires and explosions whether initiated by spark or spontaneous ignition sources occurring inflight or on the ground.

All protective measures proposed involve additional weight and certain of these also incur loss of fuel volume, maintenance, servicing, logistics and range penalties (Tables 3 and 4), trade off studies are essential.

9 CONCLUSIONS

Combat fuel system protection measures aimed at providing improved fuel containment, explosion and fire suppression are available for fitment to both military and civil aircraft.

Fuel containment and anti-misting fuels could be the key factors in reducing dynamic fuel spillage and improving occupant survivability in the case of the post crash fire.

Fire hardening of the fuselage structure and improved fire resistance of transparencies should be examined.

Aircraft fire safety and crash resistance should be taken into account in the design of new combat and civil transport aircraft and in the selection of future fuels.

Protective measures incur additional weight (direct or indirect), together with other associated penalties such as fuel volume loss, maintenance, servicing, logistics and operating costs.

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2 J.A. Macdonald, H.W.G. Wyeth: "Fire and explosion protection of fuel tank ullage." Reference 23 in Agard Conference Proceedings No.84 on Aircraft Fuels, Lubricants and Fire Safety, AGARD-CP-84-71 (1971)

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Table 1

COMPARISON OF FUEL TANK EXPLOSION PROTECTION SYSTEM WEIGHTS

System	Principal of operation	Detail	Estimated weights for various tank capacities (kg)						Main disadvantage
			Litres						
			100	250	500	2500	5000	10000	
Gaseous nitrogen	Oxygen reduction	Titanium cylinders	4.9	7.5	15.9	43.3	59.0	78.2	Logistic
Liquid nitrogen			13.6	13.6	13.6	20.4	31.5	50.5	
On board separation of nitrogen		Molecular sieve(9% O_2)	7.3	7.3	7.3	14.6			
		Hollow fibre	8.4	8.4	8.4	16.8			
Combustor gas		Titanium construction	6.8	6.8	6.8	37.8	50.2	113.5	Complexity
Halon 1301 (Pilot selection)							25*		* Limited protection at target only
Explosion suppression	Chemical inhibition		1.5	1.9	2.5	12.5	21.6	33.1	Single shot
Reticulated polyurethane foam filling	Flame quenching	Block density 30 kg/m^3	3.3	8.3	16.7	83.3	166	333	Fuel volume loss
		Block density 16 kg/m^3	1.8	4.4	8.8	44.0	88	176	
		Hollow balls 6.4 cm dia 16 kg/m^3	1.0	2.4	4.8	24.2	48.5	97	
Melded fibrous structure filling		Block density 8.5 kg/m^3	0.9	2.3	4.7	23.4	46.8	93.5	
		Cubes (60 mm) 85% v fill	0.7	1.8	3.6	18.1	36.1	72.3	

Note: No allowance made for fuel denial and engine bleed penalties.

Table 2

DRY BAY FIRE SUPPRESSION SYSTEMS

Passive system	Detail	Applicability
Dry bay fillers Foamsand fibrous structures	Melded polyester Reticulated polyether Rigid polyurethane	Uncongested voids with gap widths up to 50 mm
Powder packs	Honeycomb or reticulated cores with powder infill	Uncongested voids with gap widths up to 300 mm
Vapour packs	Honeycomb or reticulated cores with halon infill	Uncongested voids with gap widths up to 150 mm
ACTIVE SYSTEM		
Detectors and extinguishers	Optical fire detectors or piezo-electric hydraulic pressure sensors,output to pressurised extinguisher or dry powder suppressor	Dispersal systems maybe tailored to suit both narrow and larger voids considered unsuitable for passive systems

Table 3

FUEL SYSTEM PROTECTION WEIGHTS

Aircraft type	Fuel capacity (litres)	Estimated weights (kg)				
		Crashworthy fuel system	Explosion protection		Fire suppression	
			Foam filling	Molecular sieve/hollow fibre	Active	Passive
Helicopter Light	450	15 (5)*	7 (17)	10.2 (0)	2	1
	600	30				
Medium	950	35 (24)	13 (33)		10	1
	1400			10.2 (0)		
	1900	44				
Heavy	4000		44 (138)	30.6 (0)	26	22
Combat aircraft Ground attack	4000		44 (138)		20	5
Strike	7000		80 (240)		42	10
Civil transport Small	14000	576	130 (480)			
Medium	40000	1670 } Up to 20%	370 (1380)			
Large	193000	8000	1800 (6660)			

* Estimated fuel tank capacity loss (litres) shown in brackets

Table 4

FUEL SYSTEM PROTECTION - LIMITATIONS AND PENALTIES

Protected item	Protection method	Limitation and penalties
Fuselage/wing structure	Fire hardening with surface protective coatings.	Area of application severely limited due to attendant weight penalty.
Dry bays/ cargo holds	Fire suppression with active/ passive systems.	Maintenance and servicing penalties.
Fuel tankage	Explosion protection with inert gases and intank fillers.	System effectiveness dependent on aircraft operational profile, logistics penalties occur with systems other than on board gas generation. Intank fillers result in fuel volume loss and intank servicing penalties.
Fuel piping and fuel containment	Vent flame suppression with flame arrestors.	Care must be taken to avoid undue pressure drop due to ice/debris blockage.
	Crashworthy fuel systems and multicellular tankage.	Flexible tanks incur fuel volume loss as compared with integral tanks. Multicellular construction increases system complexity.
Fuel type	Anti-static and anti-misting fuel additives.	Compatibility with fuel system is essential under all operating conditions. Power requirements for degrading safety fuels and increased cost may be significant factors.
Power plant	Fire detection and suppression.	Extension of the current systems and possible improvements will involve maintenance and servicing penalties. Care must be taken to avoid false warnings.
	Debris containment with armour.	Area of application of armour severely limited due to attendant weight penalty.

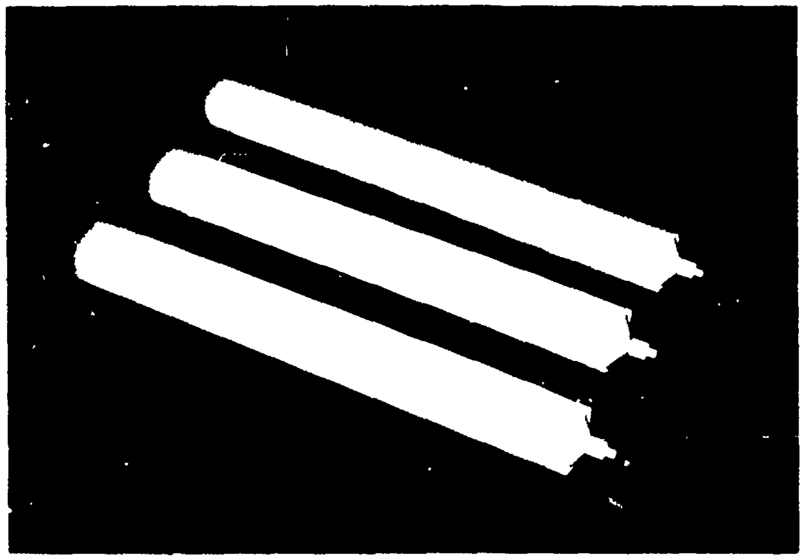


Fig 1 Reticulated foam columns

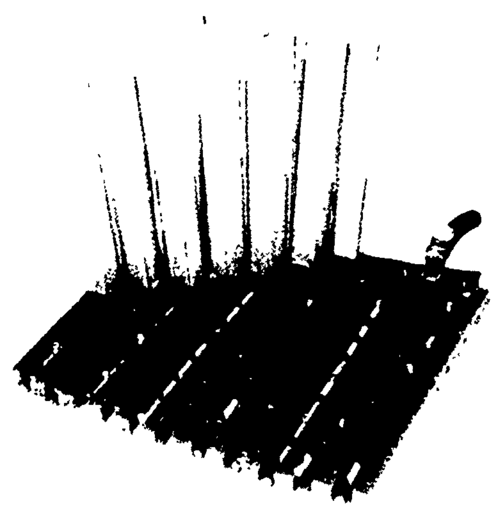
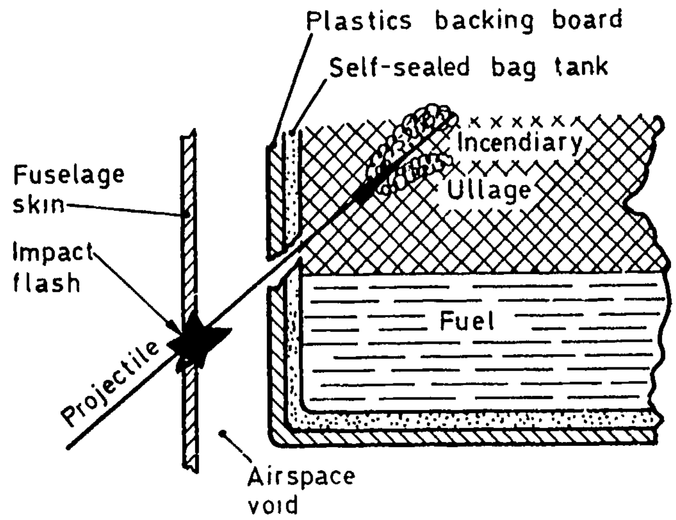
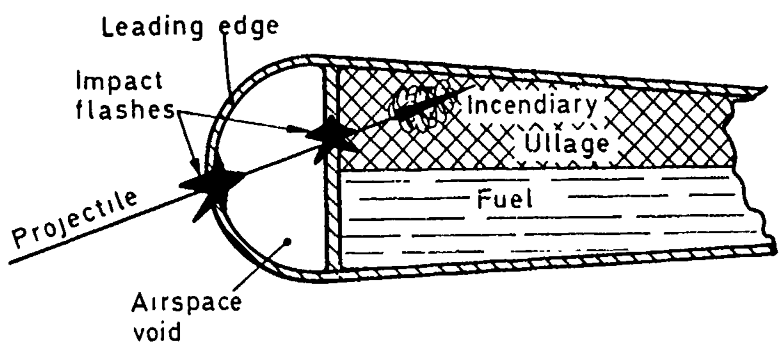


Fig 2 Fuel tank assembly

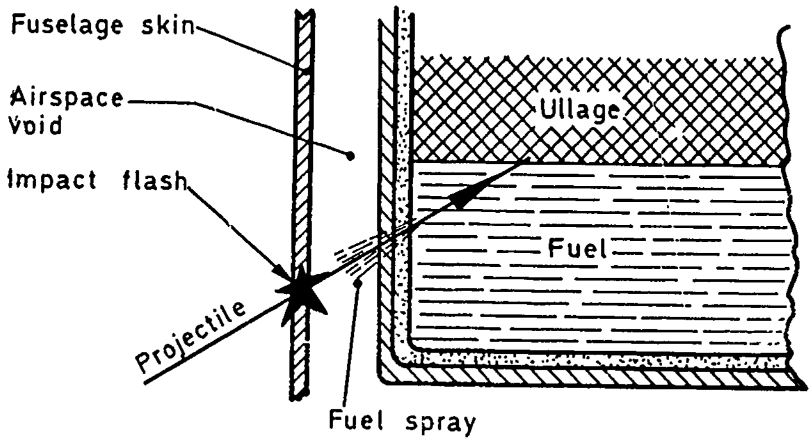


Fuselage self-sealed bag installation



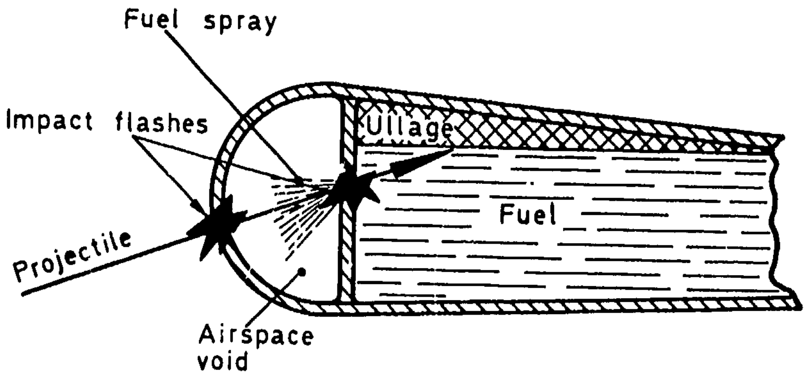
Wing integral tank installation

Fig 3 Fuel tank internal explosion



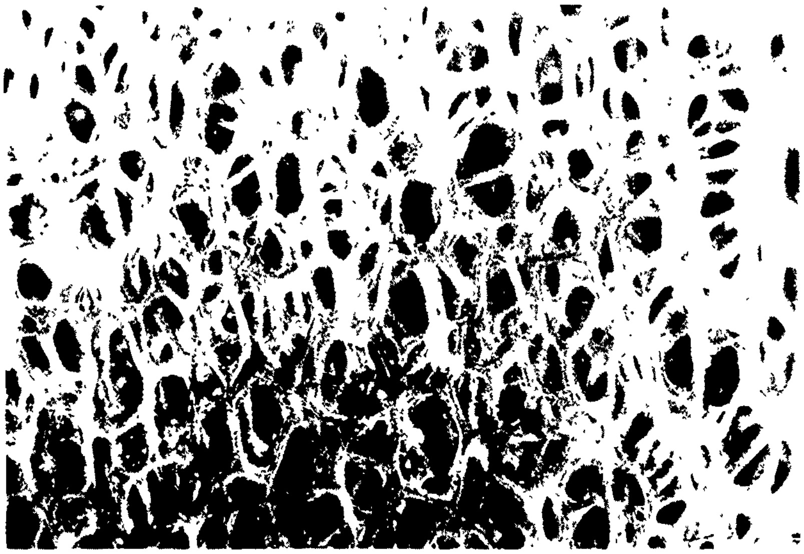
Fuselage self-sealed bag installation

Inert round - impact flash
Incendiary round - incendiary mix also released within void

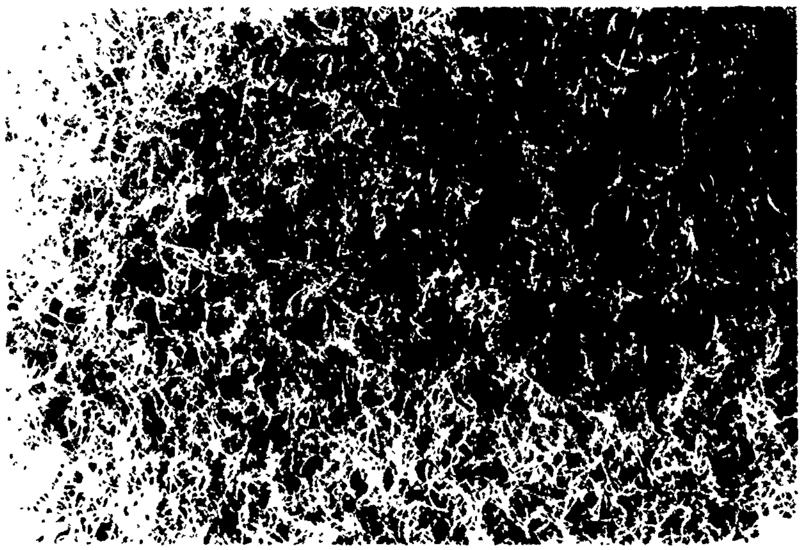


Wing integral tank installation

Fig 4 Fuel tank external fire



(a) Reticulated polyurethane foam



(b) Melded polyamide fibrous structure

(c) Expanded metallic foil

Fig 5 Intank fillers

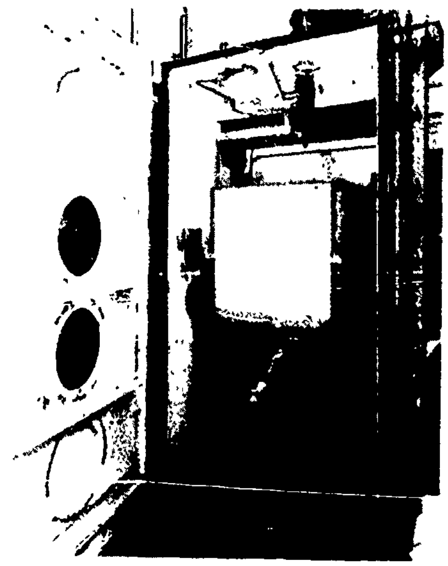
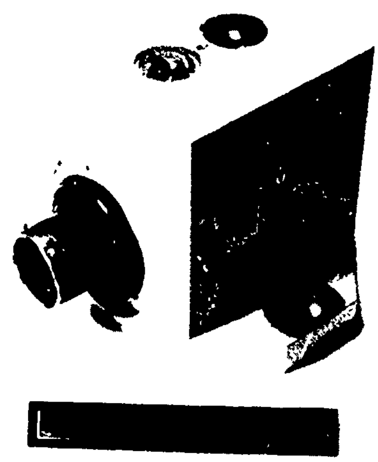
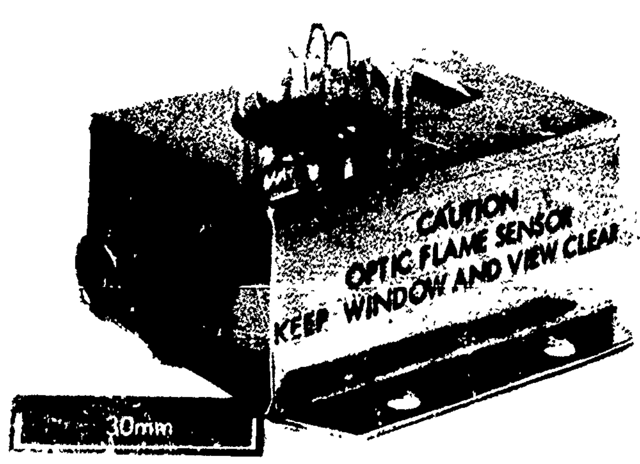


Fig 6 Fuel system evaluation of intank filler

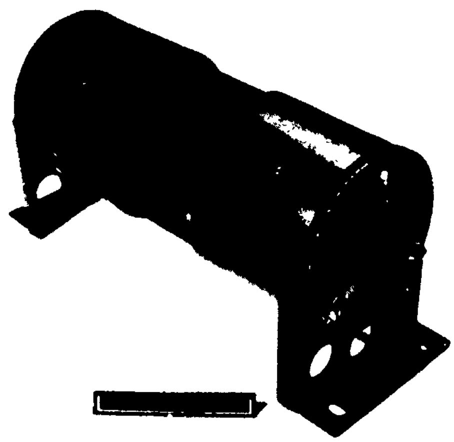


(a) Infra-red sensor

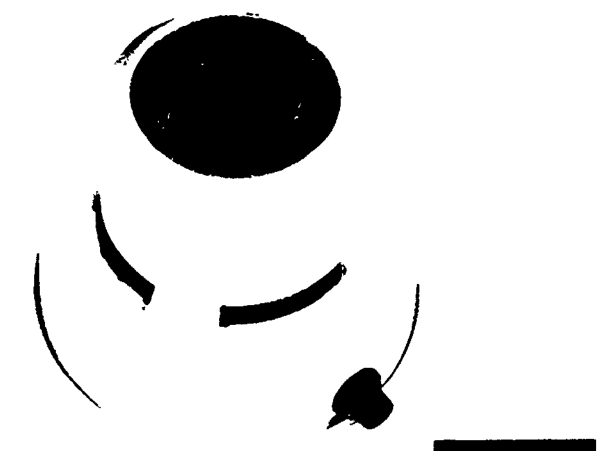


(b) Ultra-violet sensor

Fig 7 Optical fire detectors

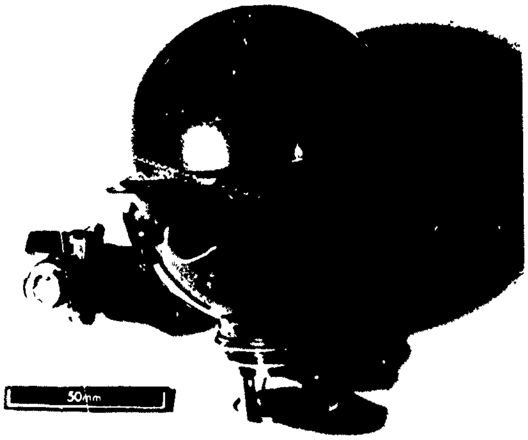


(a) Light scattering sensor

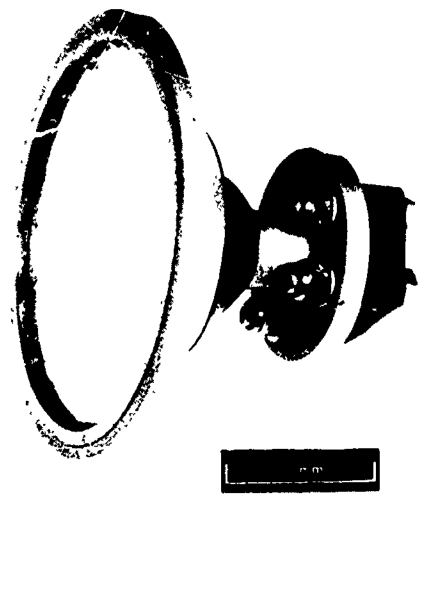


(b) Ionisation sensor

Fig 8 Smoke detectors



(a) Halon extinguisher



(b) Dry powder suppressor

Fig 9 Fire extinguishers

FIREWORTHINESS OF TRANSPORT AIRCRAFT INTERIOR SYSTEMS

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SUMMARY

This paper presents an overview of certain aspects of the evaluation of the fireworthiness of air transport interiors. First, it addresses the key materials question concerning the effect of interior systems on the survival of passengers and crew in the case of an uncontrolled transport aircraft fire. Second, it examines some technical opportunities that are available today through the modification of aircraft interior subsystem components, modifications that may reasonably be expected to provide improvements in aircraft fire safety. Cost and risk benefits still remain to be determined.

Space permits only the discussion of three specific subsystem components: interior panels, seats, and windows. By virtue of their role in real fire situations and as indicated by the results of large-scale simulation tests, these components appear to offer the most immediate and highest pay-off possible by modifying interior materials of existing aircraft. These modifications have the potential of reducing the rate of fire growth, with a consequent reduction of heat, toxic gas, and smoke emission throughout the habitable interior of an aircraft, whatever the initial source of the fire. It will be shown that these new materials modifications reduce the fire hazard not only because of their unique ablative properties, which help to contain or isolate the fire source, but also because there is a significant reduction in their characteristic flame spread, heat release, and smoke and toxic gas emissions.

SURVIVABILITY CRITERIA FOR AIRCRAFT FIRES

Significantly destructive fires, which have been encountered by transport aircraft, can be classified generally into three kinds (fig. 1): the in-flight fire, the ramp fire, and the survivable postcrash fire. Historical surveys taken over periods of 10 to 15 years for a variety of aircraft under a wide range of operating conditions have shown that the postcrash fire accounts by far, perhaps by a factor of 10, for most of the aircraft fire deaths. As indicated in figure 1 for a 270 passenger aircraft, the probable interaction of the 37,000 to 75,000 liters of jet fuel and ignition sources generated by damaged engines produces a fire source that interacts with the airframe and then with the interior systems to introduce the survivability fire parameters listed in the figure. The in-flight fire, whatever its source, can interact directly with the interior subsystems to ignite and cause them to burn.

It is a basic premise of all subsequent arguments that any vehicle interior will become a totally lethal environment if the fire source is large enough. It is also tacitly assumed that any and all material subsystems of an aircraft interior comprising organic polymeric materials (as shown as fuel load in fig. 1) can also contribute by means of (or may be limited by the fire parameters shown) to the formation of a lethal environment if the fire source and fire growth rate are sufficiently large. It is really unimportant when considering the flammability of the aircraft interior whether the fire source derives from, for example, the ignition of spilled fuel, a cargo bay fire, or arson. What is important, however, is how flammable the interior subsystems are and how large a fire source is encountered. Effects of crash impact on human survivability and of vehicle crashworthiness on the growth of the fuel fire have not been considered in this paper. Only the time rate of change in cabin temperature and the concurrent release of smoke and toxic gas from the combination of the fire source and the fire involvement of the interior have been considered as significant factors in establishing allowable egress times for passengers and crew members. It has been a goal of NASA's "FIREMEN" program to improve the allowable egress time by a factor of 2, that is, from 2.5 to 5 min, by modifying the materials used in aircraft interior subsystems to better understand the conditions imposed by postcrash fuel fire sources.

The ground rules of the SAFER Committee (ref. 1) excluded the in-flight fire case from considerations. This limited somewhat their specific recommendations concerned with the fireworthiness of aircraft interior systems, such as toxic fume hoods, and fire-fighting methods. The Federal Aviation Regulation (FAR) burner flammability test remains as a recommendation which all must agree has not been related to materials aircraft fire safety. It is reasonable to infer from the foregoing that once an interior system has been ignited with a sufficient fire source that the survival time for the in-flight case can be closely related to the allowable egress time in the postcrash fire.

The SAFER Committee has postulated that the evidence from aircraft fire death statistics makes in-flight fires relatively insignificant and that only postcrash fires deserve immediate attention. Postcrash fires cause about 30 deaths per year; recent congressional testimony (ref. 2) suggests that there have been over 300 fire deaths in in-flight fires since 1969. About 419 fatalities are attributed to survivable postcrash fires during the 1969-1978 period according to the same testimony. This recent record of in-flight events should moderate an exclusive interest in postcrash fires. SAFER made two other assumptions: (1) that the principal fire source in aircraft fire deaths in that arising from ignition of a misted-fuel cloud resulting from tank rupture during impact; and (2) that the heat, smoke, and toxic gases produced by the burning fuel are principal factors in the formation of a lethal cabin environment. One might conclude, after considering these two assumptions, that the fireworthiness of aircraft interiors may be a matter of little concern in most cases, and, indeed, current activities with antimisting kerosene (AMK) correctly reflect this hypothesis and dominate the SAFER recommendation. SAFER, however, did endorse full-scale simulation of survivable postcrash fires, using a C-133, as a means of assessing the role of the fuel fire on human survivability. Recent results from C-133 tests (to be discussed below), reported in reference 3, seem to indicate that the flammability of interior systems may be the principal factor in the allowable egress time, even in the postcrash fire. Detailed analysis of the fireworthiness of transport aircraft accidents (ref. 4) indicates that under many conditions the flammability of interior systems may be significant in postcrash as well as in-flight aircraft fires. Recent fires in both rapid ground transportation and transport aircraft suggest that under the appropriate conditions, vehicle interiors are destructively flammable, independent of the nature of the large fire source.

INTERIOR SYSTEMS FROM A FIRE POINT OF VIEW

There are two identifiable, distinct, and separate thermochemical mechanisms by which interior material systems can interact with a given fire source. These mechanisms have been defined in this paper as fire isolation (containment) and fire involvement. The first interaction depends only on the ablation efficiency of the material subsystem component; the second depends on combustion mechanisms that have been shown to depend on the pyrolysis vapor production rate and on the composition of the pyrolysis gases.

Neel et al. (ref. 5) have demonstrated, in a full-scale test with an intact C-47 fuselage, that the lethal effects of a complete burn with an 18,925-liter fuel fire source can be completely excluded from the aircraft interior by means of a lightweight organic ablative foam applied to the aircraft interior skin. No protection from fire penetration is provided by current plastic-bagged fuselage insulation. At present this ablative insulation systems approach has not been found practical by aircraft manufacturers. Kourtides et al. (ref. 6) have demonstrated in full-scale fire containment tests against simulated fuel fire sources, that ablative foams or honeycomb fillers and edge closeouts can effect as much as a fivefold improvement in the fire containment capacity of various kinds of aircraft panels, such as ceilings, lavatories, and cargo bays, while at the same time maintaining the required structural strengths without an appreciable weight penalty.

Here then is a simple, available, and producible new kind of aircraft panel concept ready for application. It is believed that inert ablation efficiency of these new panel systems may be particularly effective in controlling fires in unattended areas of the aircraft. One need only optimize (modify the foam density) the ablation efficiency of these panel structures to provide the required containment times to a designed back-face temperature, probably about 200°C for the expected heat load from probable fire sources. Specific examples of applying the ablative fire-containment method to the fire-blocking-layer concept in aircraft seating and window systems will be described further in this paper.

Fire involvement, largely dependent on material pyrolysis and flammability, is a somewhat separate matter from ablative fire containment. Fire involvement comprises the interaction of a number of factors that contribute to the generation of lethal cabin conditions - ease of ignition, flame spread rate, heat release, and smoke and toxic gas emission. All of these factors interact cooperatively to reduce the probability either of passengers escaping or surviving when trapped. These properties depend on the thermochemical properties of the basic polymer out of which the component has been constructed as well as on the size and intensity of the applied fire source. Unfortunately, most usual laboratory flammability tests (ref. 7) have been carried out at cold-wall radiant heating rates of 2.5 W/cm^2 or less. As will be discussed below, it has been found that the combustible vapor production rate at the wall of the material is the controlling rate process for all of the fire involvement factor. This controlling rate is an intrinsic property of the material and of the applied heating rate. A heating rate of 2.5 W/cm^2 is much too low to characterize materials in the usual fire environment, in which case heating rates are found to vary from as little as 0.5 W/cm^2 to as much as 14 W/cm^2.

A typical example of an aircraft panel construction is shown in figure 2. Current films, inks, substrate films, and face sheets are made up of as much as 25% of contemporary materials of low char yield polymers (to be explained below). They are characterized in terms of ease of ignition by the standard limiting oxygen index test with values from 16 to 23 (percent oxygen in the ignition mixture required for sustained burning with an ignition source of about 1-2 W/cm^2). One should expect them to burn in air under the sustained fire impact of less than 2 W/cm^2 and to burn with increasing rates as the fire source is increased.

Standard panels of this kind were evaluated by Parker et al. (ref 8) in a full-scale lavatory mock-up using a 2.5-kg hydrocarbon fuel source, with unrestricted ventilation. The fire source burned for about 10 min, with an average peak heating rate of about 8 W/cm^2, typical of a moderate aircraft trash fire. The lavatory panels, when exposed to this critical size, lead to flashover which produces a totally lethal environment in different size structures with different materials.

It was concluded from these tests that the high vapor production rate for low-char-yield materials comprising the decorative surfaces and face sheets coupled with this critical fire size combined to achieve this fatal condition. Characterization of the survivability at fire sizes with this lavatory system at less than the critical flashover fire size seems to depend on all the factors listed above that describe the total fire involvement.

Currently, attempts are being made to arrive at a "combined hazards index" or CHI (ref. 9) comprising the lethality of a material exposed to a fire source less than the flashover critical size; the index would combine the rate of heat released, the smoke obscuration, and time to incapacitation due to toxic gas emissions. So far this has required very complex testing, involving animal exposures, variable heating rates, and complex computer data reduction for fire models which depend on vehicle geometry and a presupposed fire scenario.

What is needed is a simple test for materials suppliers and users alike which would permit the selection of polymeric components for design and construction of system components on the basis of the components' enhancement of survivability in an aircraft fire. Parker and Winkler (ref. 10) showed earlier in 1967 that the anerobic char yield could be estimated from the polymer structure and the cross-linking reactions of the polymer at elevated temperatures. It may be safely inferred from the foregoing that the tools exist with which to design and synthesize polymers with any set or limiting set of fire-involvement properties that the application demands.

Later, Kourtides (ref. 11) and van Krevelen (ref. 12) showed that these char-yield rules could also be applied to calculating the limiting oxygen index (LOI) of thermoplastics in addition to the thermoset system described by Parker and Winkler (ref. 10). Kourtides et al. (ref. 13) took advantage of this rule by developing criteria for selecting thermoplastic molding components of aircraft applications by correlating a linear combination of fire involvement properties with the measured anaerobic char yield. It was also found that when atoms such as chlorine, bromine, sulfur, fluorine, or nitrogen are contained in the polymer, a simple correction in the proportionally constant relating char yield to LOI could account for the variation in flammability properties of the neat polymer. As far as polymer selections are concerned, Fish and Parker (ref. 14), first showed that as long as the polymer did not melt and flow (as do, for example, epoxides, urethanes, and phenolics) all of the significant fire involvement properties of the bulk polymers, such as flame spread rate, ease of ignition, smoke obscuration, and toxic gas production, vary in a regular way (usually linearly) with the vapor production rate of the polymer being heated. Moreover, Fish and Parker showed that this relative vapor production rate can be accurately determined by the simple thermogravimetric analysis of the anaerobic char yield.

In figure 3 it can be seen that the simple and single value of the char yield can readily be used to rank the fire involvement characteristics of individual polymers for selection of candidates for the fabrication of interior system components. It turns out that the materials flammability properties, such as net heat released and the amount of smoke and gas generated at a fixed heating rate (radiative cold wall), are all unique and regular functions of this easily measured or calculated anaerobic char yield value. It should be pointed out, however, that what one is concerned with in estimating the probability of survivability is the rate of the production of these lethal products.

Even though the char yield as defined is more or less independent of the applied heating rate, the rate of char formation and the related flammability properties are determined by the ablation rate, which in turn increases with increasing heating rate. Because the material will encounter a variable heating rate, depending on scenario, SAFER (ref. 1) has recommended that these relative rates should be determined in the Ohio State heat-release calorimeter, in which the heat release and other rates can be measured at variable heating rates. Presumably these rates then can be used to construct any desired heating rate curve to estimate the time-dependent rates of heat, smoke, and gas production. Since these rates may be expected to vary with the thermal history of the sample and with the nature of the flame chemistry, we have preferred to use a propane burner; the burner can accurately simulate the actual time-dependent heating rate functions with a reasonable simulation of the fire-source flame chemistry. Initial screening of samples may be done with radiant-panel sources at a fixed average heating rate at 5-10 W/cm^2. The measured rates in radiant-panel tests related to a real and variable heat source can be determined by a propane gas burner preprogrammed to simulate the time-dependent heating rate encountered with a real fire source. For most cases that involve the fuel fire sources encountered in aircraft fires, the flammability of materials systems can be compared by means of a radiant panel providing an average heating rate of 5-8 W/cm^2, with pilot flame ignition. These results can be correlated with the measured anaerobic char yield, which usually gives a reasonable measure of the combined hazard index. Correlations with char yields have been reported in many studies, and Hilado et al. (ref. 15) have stated that this method is adequate in 90% of the cases studied. On a char yield scale from zero (polymethylmethacrylate) to 100 (graphite), most contemporary aircraft materials are rated at less than 25, whereas the advanced materials offered in this paper all have values greater than 35. The latter are virtually nonflammable in air and produce little or no smoke or toxic gas.

The ablation efficiency in the fuel-fire environment of bulk polymers and their component derivatives is a different matter, as shown in figure 3. In this case the ablation efficiency increases with increasing char yield from about 23% to about 50%, after which it decreases abruptly. Although most of the flammability properties continue to decrease at char yields greater than 50%, it has been found that materials with char yields between 45% and 60% give the best combination of fire containment and fire involvement properties. Since it is probably true that the ablation efficiency is the principal parameter that governs the change in heat release, smoke, and toxic gas production rates, as these rates vary with applied heating rate, it is not surprising that the polymers, such as phenolics, bismaleimides, and others with char yields in the range of 45 to 60, show very low rates that change very little over an applied heating rate range from 3 to 10 W/cm^2. If it were possible to restrict the choice of advanced aircraft materials to this char yield range, which gives the best combination of fire-resistant properties, correlation of existing laboratory tests with full-scale performance would be highly simplified.

A rather simple correlation of the fire ablation efficiency of experimental aircraft panels in which the face sheets have been modified by choosing high char yield resins is shown in figure 3. The test method has been described by Riccitiello et al. (ref. 16). Here, comparable panels are exposed to a combined radiant and convective source, which has been found to correlate well with a full-scale fuel test. In the figure, the time to back-face temperature rise has been plotted as a function of the exposure time in seconds. The time required to reach a back-face temperature of 200°C has been selected to complete the relative fire ablation efficiencies of the candidate panels. It can be seen, as anticipated by the general trend in fire ablation efficiency of the face-sheet matrix resin composites, that the low-char-yield epoxies and the highest-char-yield conventional polyimides, with char yields of 23% and 70%, respectively, gave the shortest times to back-face temperature rise to 200°C; the bismaleimides and phenolics with char yields of the order of 45% to 60% gave the best performance.

Candiate phenolic and bismaleimide panels selected from this screening study were evaluated by Williamson (ref. 17), in full-scale fire-containment tests in which a variable propane burner was used to simulate the effect of actual burning of aircraft trash bags. It was found that the best fire retarded epoxy panels as baseline with face-sheet resin char yields of 23% reached a back-face temperature of 200°C in about 5 min, whereas the bismaleimide and phenolic panels with a peak heating rate of 6.5 W/cm^2 contained the simulated fire for as much as 15 min at a back-face temperature of 200°C.

On the basis of these tests, a full-scale wide-body transport lavatory was fabricated of phenolic panels (fig. 4). The fire-containment capability of this lavatory with the door closed and with the normal ventilation rate was evaluated in the Douglas cabin fire simulator (CFS). A sustained fire, which reached a peak heating rate of 12 W/cm^2 in 10 min, was started in the lavatory, using simulated aircraft trash. The fire burned itself out in about 1 hr. The effect of the fire on the lavatory is shown in figure 4. The only evidence of any lack of containment is shown in the figure as a slightly scorched area along the door edge. It is believed this slight fire penetration was a result of the limited fire containment of a small amount of polyurethane foam used at the edge of the door, a problem that can be easily corrected by replacing the polyurethane with phenolic foams. The slight damage did not propagate the fire. Otherwise the panels did not burn through or reach back-face temperatures in excess of 200°C over most of their surfaces.

No significant toxic gas was observed in the adjacent cabin area, as evidenced by the survival there of an animal (rat) test subject. A completely survivable environment existed within the cabin for 1 hr; animal subjects survived that period without adverse effects.

It can be concluded that the panels fabricated from the phenolic resins did an adequate job in containing a substantial compartment fire. However, the fact that most of the lavatory outer surface did not reach the design temperature of 200°C suggests that the fire protection ablative system was not fully exploited in this test. It is clear from various studies that the burn times and peak heating rates are controlled by the ventilation rate and the amount of fuel and its distribution in the compartment. One might say that the size of the fire in the test (fig. 4) was conservative. The simulation results with the propane gas burner support a conclusion that these panels could be expected to contain a compartment fire of a much greater severity for 3 to 5 times as long as the standard epoxy panels. The phenolic panels should be able to provide a margin of safety at least 3 times greater than the epoxy panels. This is especially important since similar panel construction is used throughout the aircraft interior where more fire sources (postcrash fires) may be encountered, for example, in cargo bays and side wall and ceiling panels.

The effects of face-sheet matrix resin type on the time required for complete fire involvement in a simulated cabin compartment were evaluated in a large-scale flashover fire test facility (fig. 5). A flashover fire test facility was constructed as a modification of the corner test described by Williamson (ref. 17). A ceiling extension panel constructed of the same materials as the wall panels was included. The propane burner shown in the corner, which had been calibrated with aircraft trash bags by metering the propane gas flow, was used as a fire source. The heating rate changes with time, as measured by calorimeters installed in the walls and ceiling, duplicated those of the aircraft trash bags. An arbitrary flash-over criterion was adopted as the time for the center ceiling thermocouple No. 57 to reach 500°C. In a baseline test with Transite (noncombustile and thermally inert), 500°C was reached in about 2 min; this value is represented in figure 6 as T3. With ceilings and wall panels constructed of standard epoxy, the critical temperature of 500°C was reached in less than 30 sec (T0) as observed on thermocouple No. 57, the process being accompanied by large amounts of dense smoke, shown in a separate test, to be largely due to the epoxy resin component of the panel. Next, a fire retardant epoxide panel was evaluated which extended the flashover time to more than 50 sec (T1). As expected with fire-retardant additives, enormous amounts of dense black smoke were generated from these panels almost immediately, but the flashover time was extended by a factor of 2.

Similar constructions were tested using the same phenolic and bismaleimide panels as those used in the fire-containment tests described by Williamson (ref. 17) using the same fire scenario. Very little smoke was observed in either test. The phenolic panels gave a ceiling temperature of 500°C in 60 sec (T2), and the bismaleimide gave a flash-over time greater than 90 sec (T3), the bismaleimide panel being somewhat less resistant to total involvement than the inert Transite panels. In this test, an improvement by a factor of 3 for the time to full fire involvement was observed in comparing the state-of-the-art epoxy panel with the advanced bismaleimide panel; moreover, there was virtually no smoke obscuration. It remains to be seen if a similar relationship will hold for full-scale testing of these advanced panels in the C-133.

It is of interest to see if the flashover times in this test can be correlated with the anaerobic char yields of the constituent resins and the respective oxygen indices. A best correlation was obtained by plotting the product of the time to flashover, T, and the applied heating rate observed at that time due to the burner fire source, as a function of the observed anaerobic char yield or limiting oxyen index. The change in the shape of the fire response curve approaches the limit for the inert Transite. It is interesting to note that the intermediate char-yield materials, the bismaleimide and the phenolic (45-60%), show the same relative ranking in this test as that observed in the fire-containment case. This suggests that not only the char yield but also the fire ablation rate of char formation (slower in the case of the bismaleimides at these heating rates) are factors in the time required for full fire involvement. Even though both face-sheet matrix resin systems produce little observable smoke and presumably low levels of toxic gas, the best panel as determined in both fire-containment and fire-involvement studies seems to be the one derived from the bismaleimide.

At present, the phenolic resin system is the one of choice mainly due to resin costs and processibility. Anderson et al. (ref. 18) have shown that a positive cost benefit can be derived from using this phenolic panel system. This report details the result of a contractual program with the Boeing Commercial Airplane Company to examine the fire characteristics of sandwich panels, using laboratory-scale test procedures. The program had the multiple objectives of improving flammability, smoke emission, and toxic gas emission characteristics of sandwich panels without sacrificing manufacturability or mechanical or aesthetic qualities of the panels.

Figure 2 shows a typical configuration of a sandwich panel considered in the Boeing program. The various laminating resins and the test matrix used for these panels are also shown in this figure.

A full matrix of testing was accomplished and the test results were combined mathematically with material and fabrication costs to arrive at a relative ranking of the candidate materials. The mathematical procedure utilized a weight distribution of parameters (fig. 7); this ranking method identified phenolic as the preferred resin system.

Figure 8 shows the contrast between flame-retardant epoxy resin and phenolic resin sandwich panels with respect to flammability, smoke, and toxic gas emission characteristics. It illustrates the improvements that phenolic resins exhibit over the baseline epoxy system.

Figure 2 is an example of a sandwich panel constructed with a phenolic resin. This construction, similar to that of a 747 part tion panel, uses Tedlar (polyvinyl fluoride) as the decorative surface

Phenolic resins have subsequently been developed further and will be used in the new generation commercial aircraft (e.g., 757 and 767). They will be utilized in a sandwich panel composite configuration, but it will be a crushed-core design concept. This provides for use of the weight advantages of sandwich panels while allowing more intricate contours to be achieved.

Figure 9 shows an example of a crushed-core sandwich panel; the panel shown is similar to that which will be utilized on the 757 and 767 aircraft.

ADDITIONAL REMARKS ON PANEL SYSTEMS AS CEILINGS

The results of the postcrash fire simulation with contemporary materials in the C-133, which will be discussed below, focus attention on the role of the flammability of ceiling panels in propagating the fire, once the fire is started by burning seats. In figure 2, it can be seen that in addition to the composite face sheets, contemporary panels also comprise a decorative surface system that consists of an outer layer of clear polyvinyl fluoride, PVF, and interlayers of additional PVF, acrylate inks, and adhesives. All of these materials are highly flammable. They are present in such small amounts in comparison with the composite matrix resin that they contribute very little to the time to flash-over in the tests already described. However, as mounted horizontally above the tests, they ignite and drip as flaming debris and promote the rapid propagation of the fire throughout the aircraft interior. Even if the new fire-resistant seat is not ignited directly by the intrusion of the fuel fire, direct contact with the ceiling structure may spread the fire rapidly.

Durable, transparent thin films - easy to process by existing decorating methods and with the same excellent maintainability characteristics as contemporary materials - have been exceedingly difficult to find. Although research at Ames has discovered a large number of high-char-yield transparent films that are finding wide application in aircraft windows and military canopies, none of them has the combination of properties required. New polymer research at Ames has identified several candidate polymers generally related to polyesters and polycarbonates that may be long-term solutions. A new high-char-yield polyether-ether-ketone (PEEK) (ref. 19) now being developed is an outstanding candidate to replace the existing polyvinyl fluoride film component. The PVF film has been found to give as little as 18% char yield with a limiting oxygen index of 16%, whereas the new polyether-ether-ketone gives values of 45% for the char yield and a limiting oxygen index of 37%, properties that are theoretically very close to ideal from a flammability point of view. This new film, intended for at least ceiling applications, has been also found to exhibit excellent maintenance characteristics. It will have to be applied with fire-resistant adhesives and inks. Two new polymers have been discovered which may serve this purpose. New fire-resistant ink and adhesive systems based on phosphorylated epoxides and tetrabromoepoxy acrylates are being developed by Kourtides, Parker et al (ref. 20) to meet these special requirements. In the short term, fire-resistant bismaleimide composites, decorated with an ablative coating or with no decorative system, may be required for the highly fire-sensitive ceiling gases.

Summarizing the panel research and technology program developed under the NASA "FIREMEN" program at Ames Research Center, we have shown that the theory, materials, laboratory tests, large-scale tests, and production-ready panels - with which it would be possible to screen, select, and provide advanced panel systems - are available. And it is known that the advanced panels have a reasonable probability of enhancing human survivability when the interior system of a transport aircraft is subjected to a substantial fire source, whatever its origin. What remains to be done to establish the fireworthiness of these advanced panels is to evaluate them in all full-scale tests of a cabin interior system in the FAA C-133 simulator, using the impact of a real fire threat drawn from likely scenarios. On the basis of heat, smoke, and toxic gas evolved, including the time to full fire involvement, it is anticipated that the increase in allowable egress time will be determined.

POSTCRASH FIRE SIMULATIONS IN THE C-133

Although planned for (ref. 21), there are no satisfactory models for the postcrash fire. Hill and Sarkos (ref. 22) have designed an empirical test that is based on three levels of severity with respect to fire penetration and ignition of the interior systems. Their purpose is to answer the question: "Does the severity of the external fuel fire so dominate the available egress time that the inherent flammability of contemporary systems contributes little or nothing to the available egress time?" Stated otherwise: What is the cost-benefit in modifying the fuel system versus modifying the interior aircraft system? It is certainly not possible to make this trade-off at this time. However, the C-133 test method provides a means of uncoupling the survivability effects of spilled ignited fuel from those of the interior materials system.

This full-scale mock-up, as described by Hill and Sarkos (ref. 22), is shown in figure 10. It comprises a carefully simulated and instrumented C-133 fuselage to permit the evaluation of the external pool fire at three different levels of fire intensity within the fuselage. A fire representing an infinite fire course is created by a 1.2- by 1.2-m (4- by 4-ft) fuel pan placed in front of the open forward door. This opening may simulate some average damage to the aircraft fuselage during a crash-survivable fire with an open door and permits radiation-only penetration of the fuselage under a zero-wind condition. The transfer of heat and mass from the fuel fire is said to be rate-determined by the direction and velocity of the wind at the door.

Only the zero-wind condition (the mildest condition) will be referenced in this paper. An evaluation of this condition, namely about 14 W/cm^2 at the doorway is found to decay to about 0.3 W/cm^2 at the aircraft centerline. The evaluation of the interior environment in the absence of interior aircraft systems suggest that between 5 and 10 min are available for the passengers to escape from the unfurbished aircraft. However, when a simulation was conducted with 16 seats in typical rows with paneling and mock-up thermoplastic occupying about 10% of the aircraft, it was found that the fire that ensued might reduce the egress time to less than 2 min.

One may draw two conclusions from the above: (1) that as far as the qualifying materials for the effect of postfire environment the bunsen burner flammability test does not represent the above; and (2) at least under these conditions, the fire involvement characteristics of the interior materials play a large role in determining the human survivability at least in this scenario.

PROPAGATION OF THE CHAIN IN THE C-133 POSTCRASH FIRE SIMULATION

A tentative mechanism for the propagation of the fire chain due to the impact of the external fuel fire has been made by Eklund (ref. 23). It has been suggested that the wool-and-nylon covered polyurethane cushions nearest the door are ignited by a radiant heat pulse with a radiative input greater than 8 W/cm^2, even in the absence of free flame. This threshold has been verified by Hartzell (ref. 24) in separate radiant panel tests. Once ignited, the fire from the seat reaches the ceiling panels; quickly thereafter the so-called "two zone effect," that is, downward radiation of the heat from the hot gas layer, ignites the remaining seats and a complete fire involvement ensues. Based on this scenario significant attention has been given to a short-term fix by applying a fire-blocking layer to the outboard seats. It is believed that the use of a highly efficient elastomeric ablative material, used for thermal protection for the extremely flammable urethane cushioning, may be sufficient.

SEAT DESIGN AND DEVELOPMENT BASED ON COMPONENT RESPONSE TO THE POSTCRASH FIRE

It is clear from the foregoing C-133 test results with contemporary materials in a zero-wind postcrash fire simulation that ignition and burning of the outboard seats seems to be the principal fire source inside the cabin. It has been shown by Bricker and Duskin (ref. 25) that the extremely rapid burning of aircraft seats is due to the polyurethane cushions of the seats. Little benefit can be obtained by making the polyurethane fire retardant. Either the polyurethane elastic foam must be replaced with a completely fire-resistant cushioning foam or the polyurethane must be protected by a compatible fire-blocking ablative material. Both of these approaches are being investigated in efforts to find ways of breaking the fire chain and restricting the spread of the fire throughout the interior of the cabin.

The ablative efficiency of foamed polychloroprene (neoprene) as a fire-blocking layer to protect military aircraft fuel tanks against external pool fires was first demonstrated by Pope et al. in 1968 (ref. 26). Foamed neoprene is currently the ablative material of choice, specifically low-smoke L-200 neoprene, because of its high charring ablation efficiency, moderate cost, and availability. Neoprene cushioning cannot be fabricated at useful densities much less than 46 kg/m^3 (6 lb/ft^3) as compared with standard polyurethane at 24 kg/m^3 (1.5 lb/ft^3). It has been estimated that replacement of all the cabin seat polyurethane seat cushioning with neoprene foam would impose a weight penalty of about 907 kg (2000 lb) for a wide-body jet aircraft. Hence, the use of the foamed neoprene as a fire layer between the fabric and polyurethane foam may be the only way in the short term to control fire propagation through the aircraft interior of contemporary design.

It has been estimated from recent preliminary tests that optimization with regard to blocking-layer thickness and position of the heat-blocked seats in the aircraft could result in a weight penalty for the wide-body transport of between 68 and 136 kg (150-300 lb). When a neoprene foam is used as a fire-blocking interlayer in a thickness of 1.3 cm (0.5 in.) between the seat covering and the polyurethane foam, it has been found that this configuration results in no fire propagation at a 2 W/cm^2 radiant heat source with a free-flame-ignition source about as well as an all neoprene seat. Surprisingly, few if any of the irritating gases normally expected from the pyrolysis of chloroprene (e.g.,hydrogen chloride) have been observed in cabin fire simulator tests. It has also been observed that the neoprene fire-blocking layer covering the polyurethane and covered with wool-nylon fabric seems to surpress the flame spread across the fabric. It may be conjectured that the low-smoke neoprene not only protects the underlying cushioning foam but also, through char-swelling and hydrogen chloride evolution, inhibits flame spread of the fabric covering. These fire-suppression mechanisms observed in the cabin-fire simulator may be of considerable importance in preventing fire propagation into the aircraft interior ceiling, as was observed in the C-133 baseline test.

A sketch of an advanced seat concept is shown in figure 11. This seat has been designed with the best material options available, both with respect to functionality and to fire resistance; it has been described by Fewell et al. (ref. 27). It takes advantage of an imide foam with a somewhat lower density than standard polyurethane but with a much reduced flammability. Since this low density polyimide foam may still require some fire-blocking protection, a neoprene foam fire-blocking layer has also been included. A wool-kermel blend rather than wool-nylon is used in this advanced seat to further reduce the flame spread from external ignition sources.

A three-seat array of this advanced seat is shown in figure 12. It is planned to evaluate seats of this kind at higher heating rates than 3 W/cm^2 in the Douglas Aircraft cabin-fire simulator as a back-up for the fire-blocking neoprene-polyurethane system, especially for the case of outboard seats.

It may be concluded that the most cost-effective option available in the short term to break the fire chain generated by the external postcrash fire as it attempts to penetrate the interior system through a damaged fuselage or open door may be the use of a neoprene fire-blocking layer in contemporary seats. Neoprene foams in the form of vonar and low-smoke L-200 are commercially available and only somewhat more expensive than currently used in polyurethane cushioning. It is believed that the weight penalty incurred by using the neoprene layer can be minimized by designing the thickness to accomodate the fire sources encountered in a survivable postcrash fire. Special material options are available using the neoprene fire-blocking layer with no significant weight penalty. Application of the NASA charring materials ablation code, CMA, is available (ref. 28) and is being modified to optimize these systems. The radiant panel facilities available in the Douglas Aircraft cabin-fire simulator and the Ames postcrash fire simulator can be used to evaluate this optimization technique.

WINDOW SYSTEMS FOR POSTCRASH FIRE PROTECTION

It has been reported by SAFER (ref. 1) that the contemporary panels of a wide-body transport aircraft provide sufficient protection to prevent fire penetration of the fuselage when exposed to an external fuel fire of very short duration. However, the present acrylate window systems shrink, as should be expected, and drop out, allowing direct fire penetration long before the failure of the airframe structure. Earlier, Bricker and Duskin (ref. 25) demonstrated that contemporary polymethyl methacrylate windows were burned through in 50 to 60 sec under the heat flux typically encountered in a postcrash fire.

Parker et al. (ref. 29) have developed physically equivalent windows, composed of a high-char-yield epoxy trimethoxyboroxine transparent polymer system, that resist burn-through for up to 10 min. Eklund et al. (ref. 30) confirmed that state-of-the-art windows do indeed shrink and fall out in less than 1 min, whereas the high-yield windows do not fall out but survive for at least 6 min.

A generalized plot of window performance is shown in figure 13. Here the back-side temperature change with time is plotted for contemporary windows, which burn through (as shown) in 1.5-2 min. It can be seen that the advanced materials provide continuing protection at times greater than 8 min. In comparing the slopes of the temperature-time plots the superior ablation efficiency of the new high-char-forming windows is apparent. In order to functionality, that is, scratch, ultraviolet resistance, etc., and provide a fire-worthy window system design, it has been necessary to apply the new window material as interlayer with fire hardened edge attachment as shown in figure 14. This type of assembly has been developed into full-scale canopies for military aircraft.

Various options have been examined to apply this fire-resistant transparent material to a conventional window system (fig. 15). It is now believed that the most effective and practical way to use the epoxy window as a fire barrier is as the secondary fail-safe inner window shown in figure 16. Of course, similar fire-resistant edge-attachment methods as shown for he military canopy will have to be applied to optimize the fire performance of these new candidate windows.

DATA BASE LIBRARY FOR AIRCRAFT INTERIOR MATERIALS

The purpose of this study is to provide NASA and the FAA with several design options for a library of data for materials that are currently or can potentially be used in aircraft interiors.

It was recognized that for many years the aircraft community has been studying the contribution of materials used in aircraft interiors to aircraft fire safety. Although the fire safety record in commercial aircraft has been continuosly improved there is an ongoing attempt to alleviate the threat of severe aircraft cabin fires with state-of-the-art technology and new material developments. It is the responsibility of government organizations such as the FAA to regulate the introduction of new materials to aircraft interior use based on the material's contribution to the fire hazard. In order to effectively regulate the use of new materials, these organizations must recognize and evaluate the potential benefit and associated costs of utilizing them in the cabin interior. However, data on the material's fire performance, cost, processing, and maintenance, which must be utilized in this evaluation, are not available in a centralized repository.

The SAFER Committee recognized the need to select materials for aircraft applications that would provide the highest performance in a fire scenario while still meeting design and cost criteria. The Committee also recognized the lack of agreed-upon standard tests and fire threat scenarios, the proprietary nature of industry materials data, the continuing development of hundres of new materials per year, and the lack of large-scale, computer-based "clearing house" or data base for these materials and their properties.

Data about aircraft materials are generated by many members of the materials and aircraft community, including material suppliers, aircraft manufacturers, and government organizations involved in R&D, testing, and the development of standards. While some of the data are published and therefore distributed to other interested groups, much of it is available only to the group generating the data. To decrease the redundancy in testing and to distribute the information required for material evaluation, the SAFER Committee agreed that a centralized repository for these data should be established by the FAA.

In addition, there are conflicting viewpoints as to which testing methods should be used in materials evaluation and selection. It is recognized that a centralized data repository would provide an improved ability to compare test results from different test methods and therefore facilitate decisions about the most desirable testing methods.

The study is organized into three major tasks aimed at generating several design options for the data base. The design options will be defined by the data contents, data suppliers, required administrative support, applicable computer software and hardware, and various plans for user accessibility.

The first task is to survey potential users of the data base and suppliers of data with emphasis on characterization of the data that is both desired and available. The kinds of data potentially to be contained with the data library include:

1. Material descriptions
2. Fire performance properties
3. Physical properties
4. Mechanical properties
5. Processing and maintenance characteristics
6. Cost information

The second task involves four subtasks aimed at estimating the requirements, in terms of manpower and cost, for configuring a data base to respond to the needs of the potential user community. Included in task 2 is a survey of applicable commercial software and hardware to select those systems which may be appropriate to the various options. This task results in a recommendation to NASA and the FAA of the most effective and efficient library configuration(s).

Task 3 reviews the anticipated applications of the materials data library and will be performed in conjunction with the first two tasks. Figure 16 shows an outline of the three major tasks and their subtasks.

The study has proceeded on schedule during the first 3 months. ECON has indicated that initial design-option descriptions and cost estimates will be completed by early November. These design options will incorporate the results of the surveys of potential data-bank users and data suppliers and the screening of commercially available computer hardware and software that are now in progress. At such time these initial options will be presented to Ames Research Center and to the FAA Test Center for preliminary review and discussion.

CONCLUDING REMARKS

It has been shown in this paper that there exists a substantial technology base for the selection, evaluation, and application of fire-resistant subsystem components that can reasonably be expected to improve human survivability in aircraft fires involving aircraft interiors. This technology can, in the short term, effect improvements in aircraft fire safety as well as provide a sound basis for further long-term improvements in new aircraft.

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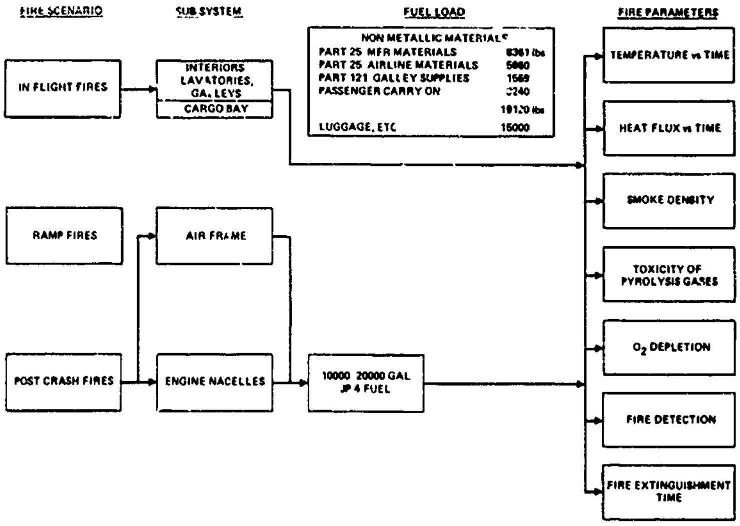
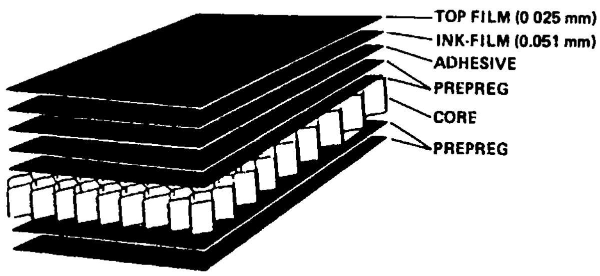


Figure 1.- Survivability criteria for aircraft fires (270 passenger aircraft). (Note: 1 lb = 0.454 kg and 1 gal = 0.378 liters.)



- CANDIDATE RESIN SYSTEMS FOR PREPREG
  - BASELINE EPOXY
  - BISMALEIMIDE
  - PHENOLIC
  - POLYIMIDE
- TESTING MATRIX
  - FLAMMABILITY, SMOKE, AND TOXICITY
  - MECHANICALS AND AESTHETICS

Figure 2.- Sandwich panel configuration.

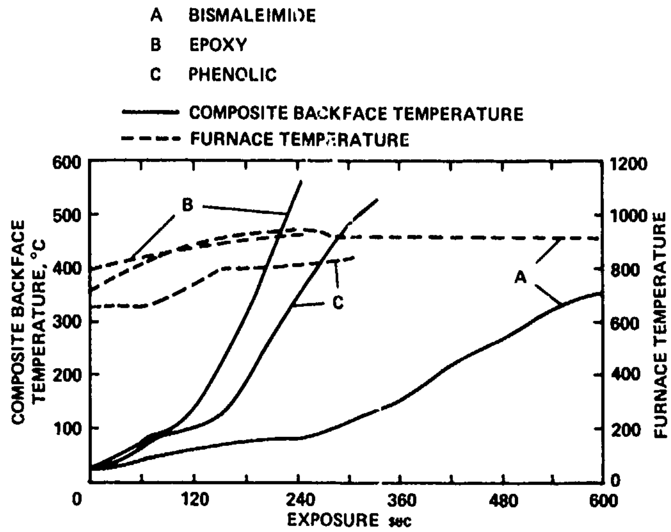


Figure 3.- Thermal efficiency of panels.

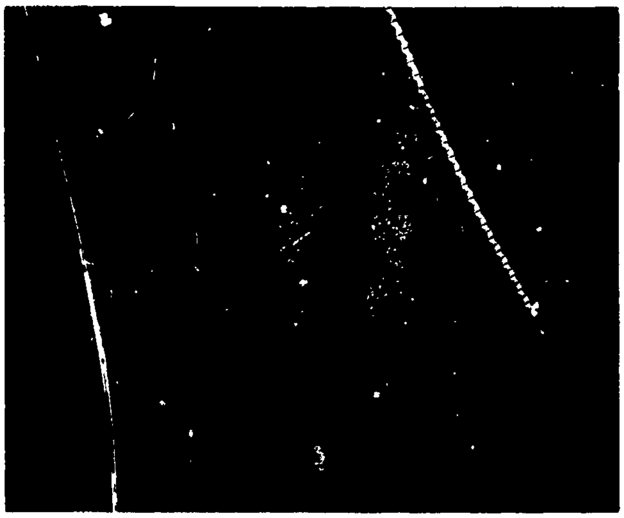


Figure 4.- Laboratory setup in cabin fire simulator.

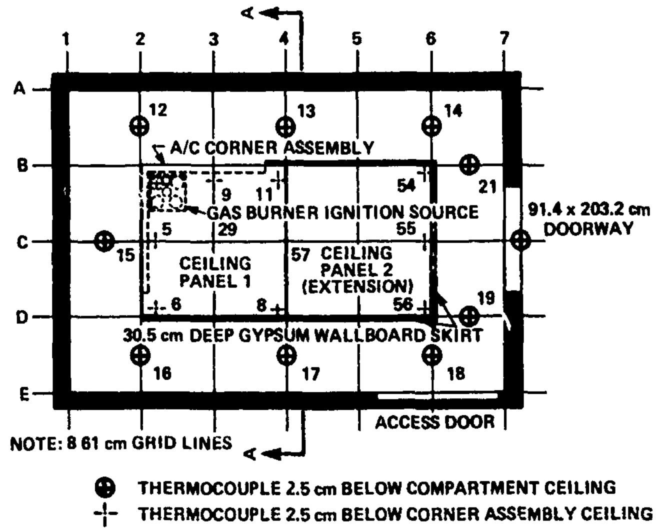


Figure 5.- Flashover test facility.

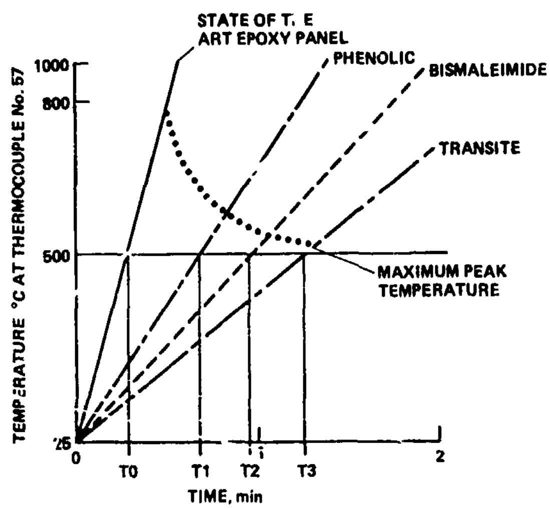


Figure 6.- Center point ceiling temperature as function of time for Transite, state-of-the-art epoxy, and advanced resins.

- **LABORATORY TESTS—WEIGHT DISTRIBUTION**
  - FLAMMABILITY—10%
  - SMOKE EMISSION—20%
  - TOXIC GAS EMISSION—10%
  - HEAT RELEASE—20%
  - HEAT RELEASE RATE—20%
  - THERMAL CONDUCTIVITY—4%
  - MECHANICAL STRENGTH—6%
  - DENSITY—10%

- **MATERIAL AND FABRICATION**
  - 15%
  - LABORATORY TESTS—85%

Figure 7.- Ranking procedure.

	BASELINE EPOXY	DEVELOPED PHENOLIC
• PROPENSITY TO BURN (LOI)		
• FACE SHEET	29.0	100^+
• BOND PLY	27.7	53.5
• SMOKE EMISSION (D_s @ 4 min) NBS		
• 2.5 W/cm2	62.8	2.5
• 5.0 W/cm2	96.5	8.4
• HEAT RELEASE (J/cm2) OSU		
• 2.5 W/cm2	177.2	126.0
• 5.0 W/cm2	512.4	96.3
• CHAR YIELD, 800°C, N_2, %	38.0	61.0

Figure 8.- Flammability and smoke.

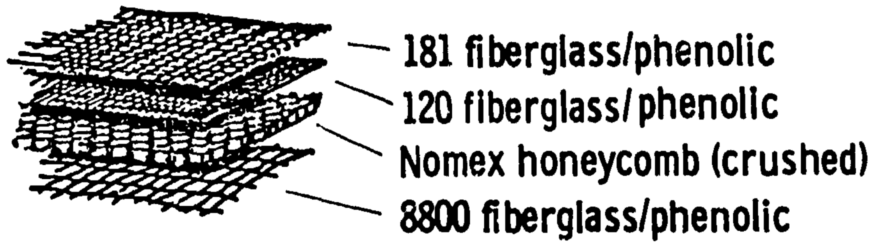


Figure 9.- Crushed core sandwich panel.

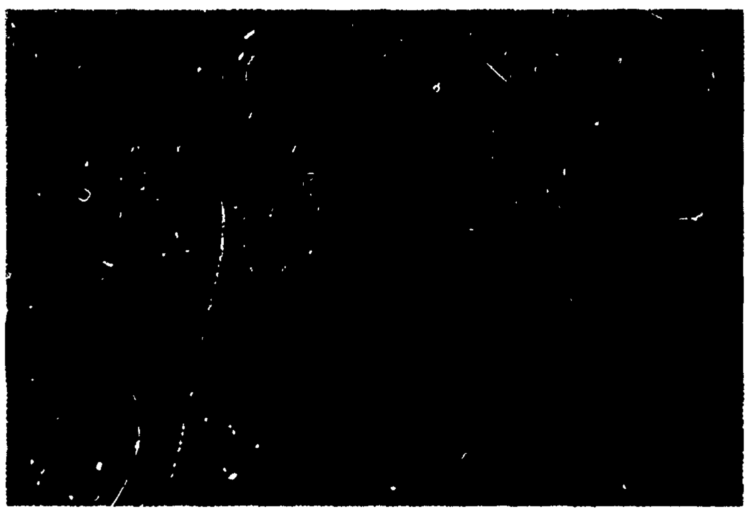


Figure 10.- C-133 wide body cabin fire test article.
(Note: 1 ft = 0.3048 m.)

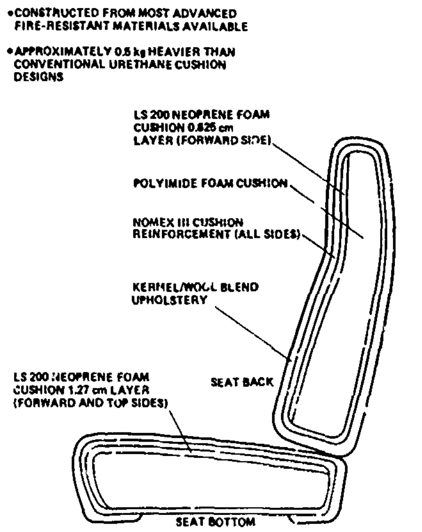


Figure 11.- NASA fire-resistant passenger seat cushion construction.

Figure 12.- Three-seat array of advanced seats.

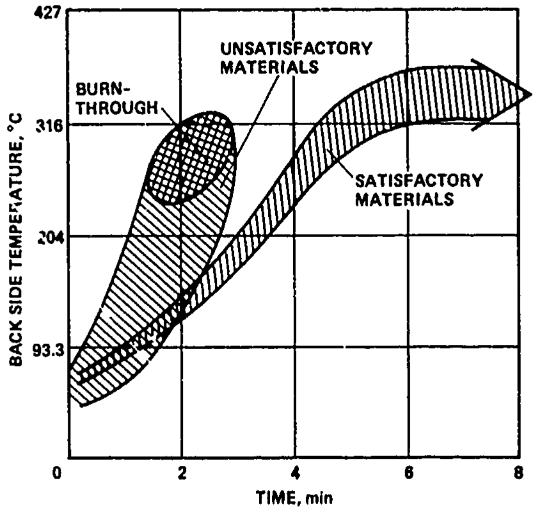


Figure 13.- General data plot of Ames Research Center's T-3 fire test results.

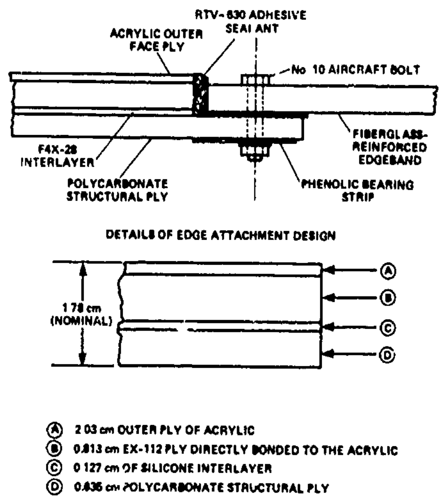


Figure 14.- Fire-resistant transparent composite.

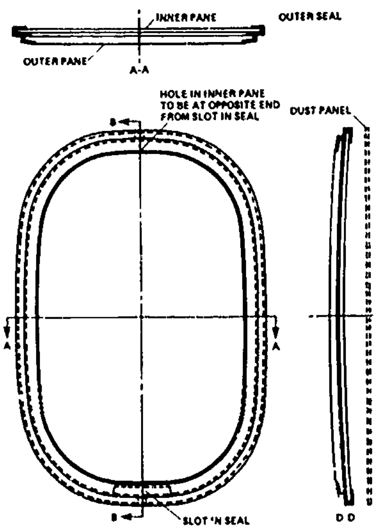


Figure 15.- Air transport passenger window.

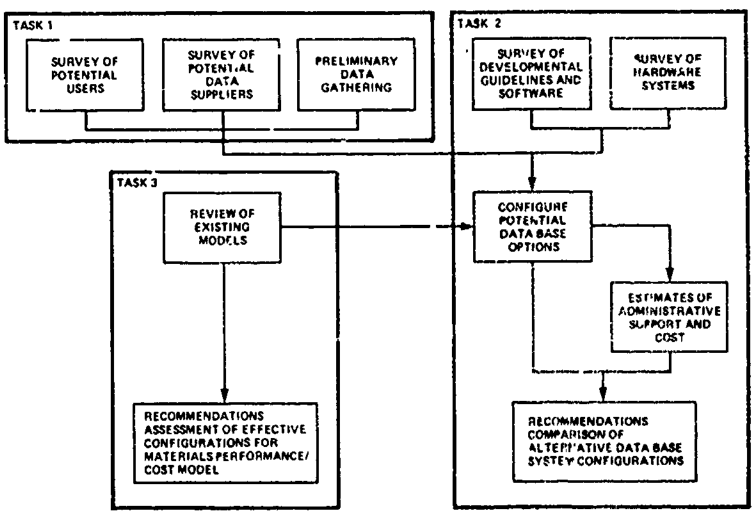


Figure 16.- Overview of study tasks.

The Development and Application of a Full-Scale Wide Body Test Article to Study the Behavior of Interior Materials During a Postcrash Fuel Fire.

by
Constantine P. Sarkos
Richard G. Hill
Wayne D. Howell

SUMMARY

Over the past 20 years, all fatalities attributable to fire in United States air carrier accidents have occurred during survivable crashes (versus in-flight fire accidents). In almost all of these cases, the postcrash cabin fire was initiated by a large fuel fire external to the aircraft. Under these conditions, the importance and role of cabin materials on survivability, in the context of and in contrast to a large fuel fire, is difficult to assess. Small-scale fire tests on cabin materials — by themselves — do not treat the dynamic range of conditions and important parameters present in a real cabin fire. Therefore, over the last 5 years, the Federal Aviation Administration (FAA) has placed increasingly more emphasis on large- and full-scale fire tests and fire modeling to understand and demonstrate the behavior of cabin materials in a postcrash fuel-fed fire.

The focal point of this work is a full-scale, wide-body test article, constructed from a surplus C-133 aircraft. This paper describes the following major elements of the development and application of the C-133 article to study postcrash cabin fires: (1) initial development, capabilities and instrumentation; (2) derivation of fuel fire test conditions based on physical modeling and large-scale fire tests; (3) characterization of cabin fire hazards arising solely from an external fuel fire without the contribution of interior materials; (4) characterization of cabin fire hazards resulting from the exposure of wide-body interior materials to an external fuel fire (the fires, by itself, would be clearly survivable over the test duration if the interior were noncombustible); and (5) evaluation of the effectiveness of urethane seat cushion fire blocking layers and improved cushioning materials over a range of test configurations. The results of the extensive tests that have been performed to date, especially over the past 12 to 18 months, are beginning to improve our understanding of the cabin hazards and important parameters associated with postcrash fire, and, by the example of seat cushions, illustrate how safety benefits can be realized by the usage of improved materials.

INTRODUCTION

OBJECTIVE

The objective of this paper is twofold: (1) describe the development and design of a full-scale test article for studying the characteristics of transport cabin fires created by a postcrash external fuel fire; and (2) describe the evaluation of the effectiveness of aircraft seat cushion fire blocking layers under large- full-scale test conditions.

BACKGROUND

Aircraft accident investigations, in most instances, do not furnish the detailed information required to identify the primary physical factors contributing to those fatalities resulting from fire. This lack of information is due, in part, to the infrequent occurrence of aircraft accidents and the usual destruction of evidence by the fire, but, more importantly, to the complex nature of the fire dynamics and hazards ultimately responsible for preventing escape by passengers and crewmembers. Therefore, although the outcome of an accident investigation may suggest the existence of a design deficiency leading to fire fatalities in a particular case, some form of controlled and well-instrumented experimentation is needed to validate the conclusions reached and the benefits of proposed improvements. The type of testing which is most convincing is that which most closely replicates the actual fire environment and aircraft geometry configuration; i.e., what has been termed a full-scale test. The utilization of full-scale tests is a major and integral aspect of the aircraft fire safety program conducted by the United States (U.S.) Federal Aviation Administration (FAA) (reference 1). This paper will describe the development and application of a full-scale cabin fire test article for studying the behavior of interior materials subjected to an external fuel fire.

A number of organizations, including the National Transportation Safety Board (NTSB), which has the responsibility for investigating civil aviation accidents in the United States, have analyzed the incidence of aircraft accidents accompanied by fire. A study by NTSB for the period 1965-1974 estimated that 15 percent of all fatalities in U.S. air carrier accidents were attributable to the effects of fire (reference 2). In all instances, the cause of the fire was the result of aircraft crash impact with the ground. Moreover, in most cases, the fire originated from the ignition of jet fuel released from fuel tanks damaged by the crash impact.

A much smaller number of fatal accidents have occurred in U.S. manufactured aircraft operated by foreign carriers as a result of accidental fire erupting inside the fuselage while the aircraft was in-flight. These in-flight fatal fires consist of a Varig 707 in 1974, a Pakistani 707 in 1979, and a Saudia L1011 1980, combining for a total of over 500 fatalities. As a consequence of the two recent accidents, particularly the Saudia L1011 which resulted in 301 fire fatalities, more emphasis is now being placed within the FAA's Cabin Fire Safety Program on in-flight fire problems.

It is generally agreed that ignition of jet fuel represents the greatest potential danger in aircraft crash accidents. No other conclusion seems possible when one considers that jet fuel is extremely flammable and is carried in large quantities in modern jet transports; e.g., the fuel tanks capacity of an L1011 is 23,000 gallons (reference 3). In accidents where large quantities of fuel are released and ignited, and where the integrity of the fuselage is damaged to a degree that enables major portions of the cabin to be directly subjected to the fuel fire, the dominance of the fuel fire is clear. However, accidents do occur with relatively small quantities of fuel spillage, or none at all, and with the fuselage primarily intact, that result in a cabin fire leading to fire fatalities. These accidents are part of a classification of accidents defined as survivable; i.e., those accidents in which one or more of the occupants survive the impact. In an FAA study for the period 1964 to 1974, it was estimated that 39 percent of the fatalities were attributable to fire in survivable accidents (reference 4).

It is difficult, if not impossible, to assess the role of a particular interior material, or materials, in gene..l, on the number of fatalities in crash accidents accompanied by fire. Numerous factors are known to affect the behavior of a material in a fire (reference 5), while the present status of fire technology does not allow for the prediction of the combined effect of each factor on the overall threat to cabin occupants under a given fire condition. Nevertheless, there does exist both direct and indirect data of the importance of interior materials on survivability during a postcrash cabin fire. Of a direct nature, is the measurement of high levels of blood cyanide in some accident victims (reference 6). These measurements have been incorporated into U.S. accident investigations since 1970. However, the relationship between cyanide levels in blood samples taken from accident victims to the concentration of cyanide to which the victim was exposed to during the fire has been questioned (reference 7). Another form of direct data is the fact that although most crash accidents are accompanied by fuel spillage, several fatal accidents have occurred with insignificant or no fuel release. For example, at Salt Lake City in 1965, a 727 crashed and caught on fire as the result of a severed fuel line beneath the cabin floor. The initial fire consisting of a relatively small quantity of spilled fuel was probably not life threatening in itself, but was of sufficient intensity to ignite the cabin interior, which resulted in 43 fatalities (reference 8). More recently, a 747 crashed in Seoul, Korea, in 1980, without any fuel spillage, yet the ensuing fire killed 15 people. More of an indirect nature of data is the recognition that an aircraft cabin is an enclosure with limited egress, high loading of plastic and synthetic interior materials, and high occupancy density. Past large-scale tests conducted in the United States on simulated cabin interiors or mockups (references 9, 10, and 11) have demonstrated that hazardous and fatal conditions will arise from ignition of interior materials with the development of a self-sustaining fire. In the laboratory, a wide range of heat, smoke, and toxic gas levels have been measured during testing of in-service materials subjected to intense fire exposure (reference 12). These test data gathered under specific a.d, perhaps, not completely realistic conditions indicate the potential dangers of burning interior materials.

Complexity of cabin design is one of the many factors that make it difficult to determine the importance of interior materials on postcrash cabin fire survivability. The cabin interior is completely lined with multi-layered materials and furnished with hundreds of seats. Each component is selected with due consideration given to fire safety, functionality, durability, processability, cleanability, economics, and, of increasing importance, weight. Current FAA regulations specify that all major components "self-extinguish" after a prescribed exposure to a small flame (reference 13). Moreover, at their own initiative, the airframe manufacturers strive to select materials with low-smoke emissions and low-flame spread rate. One manufacturer also screens materials for emission of specified toxic gases. Despite apparent differences in design goals and philosophy, the cabin materials used by the three major U.S. airframe manufacturers are very similar. The composite panels which constitute the bulk of the sidewalls, stowage bins, ceilings and partitions are basically composed of a Nomex™ (aramid) honeycomb core with fiber glass facings impregnated with epoxy or phenolic resin and a decorative laminate composed of Tedlar™ (polyvinyl flouride) layers or Tedlar and polyvinyl chloride layers. A greater variety of materials are used for floor coverings and seat cushions, which are selected by the airlines, but are typically wool pile carpet and cushioning composed of flame retardant (FR) urethane with a wool (90 percent)/nylon (10 percent) upholstery cover. A full-scale test configuration should include, at least, the major cabin usage categories; i.e.,carpet, seats, sidewall panels, stowage bins, and ceiling panels.

From a practical necessity, aircraft materials are and should be selected based on the results of small-scale fire tests. However, it is generally recognized that small-scale test results do not reflect the behavior of a material in its end-use application under realistic fire conditions. Therefore, until more realistic and meaningful small-scale tests are developed, the FAA, as well as many other organizations engaged in fire testing, is relying more heavily on large-scale tests and, to a much lesser degree, full-scale tests for materials evaluation. Full-scale tests are usually performed for more far-reaching reasons; namely, define the nature of a perceived fire problem, identify governing parameters, bracket fire conditions, examine the relevency of small-scale test results, and demonstrate the benefit of improved material or fire management systems.

In the past, the number of fire tests consisting of exposure of a realistically-furnished cabin test article to a fuel fire have been small in number (reference 9, 11, and 14). Each of these test programs were deficient in one or more of the following manners:

(1) Instrumentation was incomplete or improper (e.g., absence of smoke measurements or test animals, improper sampling of reactive acid gases);

(2) The test article was not fully protected to allow for multiple tests, causing the results to be inconclusive or unconvincing;

(3) The fuel fire was unrealistic in terms of size (too small) and position (placement was inside the fuselage). The effect was to exaggerate the contribution of fuel-fire smoke to the cabin environment and to subject the interior materials to unrepresentative low levels of radiant heat;

(4) Precautions taken to negate the effect of random ambient wind, which has a pronounced and, sometimes, dominant effect on external fuel fire penetration through a fuselage opening (references 15, 16, and 17), were ineffective. Therefore, the effect of the fuel fire with regard to heat exposure of the interior and its contribution to cabin hazard levels was not identical from test to test; and

(5) Protection of the test article interior with sheet metal probably created higher wall heat loses than would have been encountered with a real interior. Thus, the wall loses could have far exceeded the levels measured in enclosure fires; i.e., 50-95 percent of the total energy released by the fire (reference 18). None of the test articles simulated a wide-body cabin. In the development of the cabin fire test article described subsequently in this paper, an attempt has been made to rectify the problems, enumerated above, that were encountered by earlier investigators.

The FAA convened the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee to "examine the factors effecting the ability of aircraft cabin occupants to survive in the postcrash environment and the range of solutions available" (reference 19). The committee approved the objectives set forth by FAA in its program plan (reference 1) for full-scale cabin fire testing. After examination of the contemporary makeup of aircraft cabin interiors, the committee concluded that a near term solution was available to protect or replace the FR urethane used in seat cushions, which was believed to be the most flammable of all the interior materials used is large quantities. The second part of this paper describes the evaluation of seat cushion blocking layers and improved foam cushions under large- and full-scale test conditions.

Although the potential flammability of flexible urethane foam has been recognized for 10 years (reference 10), it has only been until the last several years that more fire-safe and practical alternates have emerged. While neoprene foam has always possessed excellent flame resistance, earlier formulations were extremely smokey and heavy. The development of LS-200 represented a marked improvement in neoprene technology, by reducing smoke emissions and weight and improving physical properties (reference 20). Nevertheless, the reduction of neoprene foam density to the 7-8 pounds per cubic feet range was still prohibitively high for the aviation market. In order to retain the cushion properties of urethane without the weight penalty of a full neoprene cushion, the concept of a fire blocking layer encasement was developed.

By design, the blocking layer encasement inhibits or prevents the fire involvement of the flammable urethane foam underneath. A commercial foam fire blocking layer was developed in the mid 1970's and given the trade name Vonar™. Extensively evaluated by FAA and others, Vonar is a thin neoprene foam layer that is heavily treated with flame retardants (approximately 40 percent by weight). A number of mechanisms contribute to its fire blocking behavior, but, most important, is the formation of a stabile and strong char when it is exposed to heat or flame. The insulative properties of the char, of course, significantly reduce the rate of heat transfer to the urethane foam sublayer. Although Vonar had been demonstrated to be highly effective against moderate ignition sources, such as newspaper or wastebasket fires (reference 21), or fires likely to occur in rapid transit vehicles (reference 22), the FAA test program was the first to realistically subject the material to the intense radiant heat produced by a large fuel fire.

DISCUSSION

DESIGN OF FULL-SCALE TEST ARTICLE

The survivable postcrash fire scenario selected for study consisted of an intact fuselage with open doors, as might exist during evacuation, and an external fuel fire adjacent to an opening. Selection of the scenario was based on creating a realistic postcrash condition with an external fuel fire rather than a fuel fire within the cabin which is an easier test to perform but is less realistic. Moreover, it was believed that placement of the fire outside the fuselage would more properly balance the cabin hazards from the fuel fire and burning interior materials. Another important aspect, as discussed later, was to develop a test fire that would recreate the intense radiant heat produced by a large fuel spill fire. An accident occurred after the fire scenario was conceived which was a near duplicate, attesting to the realism of the scenario (reference 23).

The full-scale test article was a modified surplus C-133 aircraft. The important dimensions and overall layout are shown in figure 1. The cross sectional area is simular to, although slightly smaller than, a wide-body jet cabin. An interior volume of 13,200 ft^3 is representative of a wide-body jet. Reference 15 describes in detail the test article design.

The test article was designed for fire durability to allow for the conduct of numerous tests. This was accomplished by stripping the interior of all combustibles, lining the inside surfaces with noncombustible ceramic and fiber glass materials, and installing a CO_2 total flooding, fire protection system. It was believed that the ceramic/fiber glass materials provided for more realistic wall heat transfer than sheet metal. The test article has withstood approximately 150 tests, although on several occasions extensive repairs had to be made.

The opening adjacent to the fire was a wide body type A door opening. However, the opening was treated as a rupture rather than a door; i.e., seats are placed in the opening. This size opening was selected because descriptive information on fuselage rupture size from actual accidents was found to be lacking.

A full-scale fire test facility houses the test article. A specially designed ceiling allows for the setting of large fuel fires inside the test bay. The facility provides an environment that is basically isolated from fluctuating ambient winds, which can destroy test repeatability and make test results analysis very difficult, and allows for testing throughout the year under all weather conditions. A large fan can simulate a range of wind speeds at the fire door, providing the flexibility of varying, as desired, the degree of fuel-fire flame penetration into the cabin. Figure 2 is a photograph of a typical fire test with the facility shown in the inset.

The C-133 test article is extensively instrumented to measure the major hazards produced by a cabin fire at various cabin locations as a function of time. The most extensive measurement is that of air temperature; a series of thermocouple poles on the fuselage centerline are located throughout the cabin. Gardon gage-type calorimeters, primarily clustered around the fire door, measure the radiant and convective heat flux from the jet fuel fire and ensuring cabin fire. Smoke density is measured by light transmissometers, consisting essentially of a light source and photoelectric cell receiver. Gas concentrations are measured by continuous analyzers and from post-test analysis of batch samples taken at regular intervals during the test. The gases analyzed continuously at four cabin locations include carbon dioxide (CO_2), carbon monoxide (CO) and oxygen (O_2). The remaining gases analyzed from batch samples consist of two classes: acid gases (e.g., hydrogen fluoride (HF), hydrogen chloride (HCl), etc.) and organic gases (e.g., hydrogen cyanide (HCN), etc). The acid gases, particularly HF and HCl, are analyzed by ion chromatography of samples collected in small tubes filled with glass beads that are coated with a sodium carbonate solution. The organic gases, particularly HCN, are analyzed by gas chromatography of samples collected on Tenax™ tubes. A detailed description of the analytical methodology for the acid and organic gases is contained in reference 24. Exclusive of the gases analyzed from batch samples, the cabin hazard measurements are recorded on a computer data acquisition system, and converted into engineering units and plotted after completion of a test. Cabin fire growth is monitored during a test by video coverage. Color photography documentation includes 35mm sequential photographs at 5-second intervals, and 16mm movies.

DERIVATION OF FUEL FIRE TEST CONDITIONS

Since the quantities of jet fuel potentially involved in a postcrash fire are enormous, the realism of past full-scale fire tests utilizing small amounts of fuel was questionable. An important design goal for the C-133 test article was to derive a test fuel fire of intensity representative of a large fuel fire. Past studies of the burning behavior of pool fires indicated the dominance of thermal radiation, as compared to convection, for pool fires above 3 feet in diameter, radiation was relatively invariant at approximately 14 British Thermal Units per square foot per second (Btu/ft^2-sec) (reference 25). Of concern, however, was the amount of radiation into a cabin interior from a large fuel fire adjacent to a type A door opening. Therefore, a study was performed using models of the C-133 test article of various diameters, subjected to a fuel fire of width equal or greater to the model diameter (reference 26). The study was performed indoors to eliminate wind as a factor. It was determined that the radiant heat flux on the fuselage symmetry plane at the fire door station at an elevation of one half the door height was 1.8 Btu/ft^2-sec for an infinite fire and zero wind conditions. In addition to establishing a design goal for the C-133 test fire, the model tests in conjunction with a mathematical analysis of the radiant field inside the fuselage, demonstrated the presence of severe radiant heat gradients within the fuselage enclosure (reference 26). Thus, it became evident that, during its initial stages, an interior fire would be highly localized, and that at relatively small distances away from the fire the radiant heat flux would be virtually zero.

In order to validate the aforementioned modeling results, a surplus DC-7 aircraft with a fuselage opening scaled to the C-133 opening was subjected to a 30-foot-square pool fire (reference 16). Figure 3 contains a comparison of the symmetry plane heat flux measured during three tests with the modeling value of 1.8 Btu/ft^2-sec. As shown, a reasonable agreement was achieved between the two tests performed under calm wind conditions and the modeling prediction for zero wind. With a wind fluctuating from 4-10 miles per hour (mph), the measured radiant heat flux undulated above the modeling prediction because of the intermittent penetration of flames into the cabin caused by the winds. The increase in radiation is due both to the larger flame surface emitting heat and the smaller distance between the flame surface and measuring calorimeter.

In the C-133 test article, the fuel pan was located at the bottom edge of the opening, rather than on the ground, in order to best assure that a solid flame surface would cover the entire opening, as would result from a large ground fire. Initial tests with a 4-foot-square pan, which was slightly wider than the opening, proved that this pan size was inadequate due to incomplete flame coverage over the opening, resulting from "necking" of the fuel fire. Subsequent tests were performed with progressively larger pan sizes, and adequacy of the pan size was rated in terms of the completeness of flame coverage over the opening and closeness of the cabin symmetry plane radiation to the modeling prediction for an infinite fire. A pan that was 8 feet wide and 10 feet long completely covered the opening with flames and produced a symmetry plane heat flux of 1.5 Btu/ft^2-sec (reference 15). Although this pan size produced radiation at the symmetry plane which was slightly less than the level expected from an infinite fuel fire, it was obviously representative of a large fuel fire and was thus selected for the "standard" C-133 fuel fire. Moreover, it was feared that a larger fuel fire might jeopardize the safety of the facility housing the test article or, perhaps, cause the early destruction of the test article itself. In a typical fire test, 50 gallons of fuel are placed in the fuel pan atop a water base to assure uniform fuel depth throughout the pan. This fuel quantity assures an unwavering [illegible] or at least 4-1/2 minutes, which is the usual test duration (reference 15).

A protective covering of steel sheeting over a fibrous ceramic matting prevents melting of the C-133 aluminum fuselage skin adjacent to the fuel fire. This protective measure, which provides an opening of unchanging area for fuel fire penetration into the interior, does not detract from the realism of the test article. During an actual wide-body accident, a major fuel fire burned for an estimated 2 - 3 minutes, before extinguishment, without fuel fire penetration into the cabin (reference 23). Therefore, for a wide-body aircraft exposed to a major fuel fire for 3 - 4 minutes, it is likely that the fuel fire hazards passing through an initial opening will far exceed the increase in hazards as the opening enlarges.

CABIN HAZARDS CREATED BY THE FUEL FIRE

In order to understand the role of interior materials in a cabin fire arising from an external fuel fire, it is necessary to first examine the effects of the fuel fire alone. This was accomplished by setting a large series of fuel-fire tests with the C-133 interior completely devoid of interior materials (reference 15). The tests were performed outdoors with the test article configuration shown in figure 1 and the primary variables were ambient wind velocity (uncontrolled) and fuel-fire size. In order to examine the wind conditions of interest, which were winds of a relatively low speed (0 - 5 mph) and in a direction to cause flame penetration into the interior, tests were run in the early morning when weather conditions were favorable.

Wind conditions were found to have a dominant effect on the rate of hazard development inside the cabin. This conclusion was also reached in related studies where the effect of door opening locations away from the fire, relative to the wind direction, were also found to be an important factor (references 16 and 17). The effect of wind speed on cabin temperature is shown in figure 4 when the C-133 test article was subjected to an 8- by 10-foot fire upwind of the fuselage. Except for the low wind test (1.5 mph), the trend for the most part was to have higher cabin temperatures as the wind speed increased. The principle implications of this finding are twofold: (1) for a specific aircraft/fuel-spill crash configuration, the cabin hazards caused by burning fuel vis-a-vis burning interior materials are highly dependent on ambient wind and cabin draft conditions; and (2) for the C-133 test configuration, the degree of fuel flame penetration into the cabin, and the resultant fire exposure of interior materials near the fire opening, can be adjusted over a wide range of values by utilizing an artificial wind (fan). The small increase in cabin temperature shown in figure 4 under zero wind is the result of a significant portion of the fuel fire products, entering the cabin, becoming entrained back into the fire. The insignificant temperature rise for the zero wind case is also indicative of the results when the fuel fire is downstream of the fuselage (references 15 and 16); i.e., minimal cabin hazard accumulation even though the radiation into the cabin is intense.

The relationship between convective heating (and smoke and gas accumulation) within the cabin and radiative heating for a given wind speed was found to be dependent on fuel-fire size (reference 15). Because flame bending increases with decreasing fire size for a given wind speed, a small fire size (e.g., 4- by 6-feet) will create greater heat and smoke accumulation inside the cabin but less radiative heating than a larger fire size (e.g., 8- by 10 feet). Beginning with this experimental finding, the subsequent discussion is an analysis of the possible ramifications of the utilization of small fuel pan fires in full-scale tests. Since the amount of heat and smoke produced by interior materials increases with the level of radiation, rather than of convection inside the cabin, the proportion of heat and smoke accumulation inside the cabin from burning fuel vis-a-vis burning interior materials is greater for smaller fuel fires. Thus, the use of unrealistically small fuel fires for test purposes because of their ease of handling may produce misleading results. A small fuel fire will create higher cabin hazards from the fuel fire than might exist from larger fires, but will not cause the interior materials to burn as extensively as might a larger fire.

Tests performed with the C-133 test article devoid of interior materials indicated the prominence of certain cabin hazards over others when the fuel fire is the dominant threat. In tests with significant flame penetration into the cabin, elevated temperature exceeded human tolerance limits and smoke obscured visibility; however, CO concentrations were extremely low and clearly nonhazardous. Since high levels of carboxyhemoglobin are often measured in blood samples taken from aircraft fire victims (reference 6), in light of the C-133 test results, and without consideration of other scenarios, it appears as if this finding cannot be explained in terms of a dominant fuel fire. The source of high levels of carboxyhemoglobin in some fire accident victims may have been CO produced by burning interior materials.

CABIN HAZARDS CREATED BY BURNING INTERIOR MATERIALS

In order to study and measure the full-scale hazards of cabin interior materials subjected to an external fuel fire, a section of the C-133 test article, centered at the opening adjacent to the fuel pan, was lined and furnished with wide-body type materials. Samples of the various materials were tested and determined to be, as required, compliant with FAA flammability regulations prescribed in Federal Aviation Regulation (FAR) 25.853 (reference 13). As shown in the cutaway isometric drawing in figure 5, the materials were arranged in a realistic fashion. The following summarizes the materials' loading: (1) 12 flat, honeycomb composite panels, each 4 by 6 feet, comprised a 24-foot-long drop ceiling; (2) 6 lengths of honeycomb composite overhead stowage bins were mounted on both sides of the cabin; (3) 8 contoured honeycomb composite sidewall panels with window reveals, each 3.3 by 5.5 feet, were fastened to the insulated inner fuselage; (4) a total of 21 seats, including 6 doubles and 3 triples, composed of wool (90 percent)/nylon (10 percent) upholstery covers and FR urethane cushions, were arranged into 3 rows to form a dual aisle interior; and (5) a wool (100 percent) pile carpet was placed over the aluminum-faced cabin floor. The ceiling panels and carpet were new, while the sidewall panels, stowage bins, and seats were obtained from refurbished wide-body aircraft.

The materials were subjected to a zero wind fuel fire. This condition was selected because the cabin hazards solely arising from the fuel fire would be minimal and clearly survivable as shown in previous test (see figure 4). In this manner, the cabin hazards with materials installed in the test article would be unmistakably produced by the burning materials and not by the fuel fire.

A revealing account of the fire growth inside the cabin was obtained from the color photographic coverage, including 35mm motorized stills and 16mm movies. Examination of these films demonstrated that for approximately 2 minutes, the cabin fire was limited to the area in the immediate vicinity of the fuselage opening adjacent to the fuel fire. The outboard double seat at the fire opening was almost completely engulfed in flames, as was the back of the outboard seat forward of the opening and the front of the seat behind. Fire had not progressed to the triple seats comprising the center section, although some smouldering was evident. Also in evidence was intermittent flashing in the smoke layer under the ceiling by the opening. Although the heavy smoke obscured the upper cabin, the high temperatures recorded in this area and the existence of flashes indicated that ceiling and stowage bins near the opening were pyrolyzing and, perhaps, burning. At approximately 2 minutes, within a matter of 10 seconds, or less, the remaining interior materials were suddenly set aflame or underwent pyrolysis. This event has been observed in many types of enclosure fire tests and has been given the name "flashover." Photographs taken at 5-seconds intervals shown in figure 6, illustrate the suddeness and totality of the flashover.

The major hazards produced by the cabin fire, aft of the galley partition, are shown plotted as a function of time in figure 7. The survivability is of interest in this section of the cabin because (1) the evacuation process is usually in a direction away from the fire origin and (2) in some past accidents victims hav been found clustered near exits.

The occurrence of flashover indicates that conditions throughout the cabin will become nonsurvivable within a matter of seconds. Of concern, thus, is whether any of the preflashover hazards were at a level to impair or prevent escape. An examination of figure 7 indicates that the acid gases HF and HCl accumulated in the aft cabin at least 1 minute before any of the remaining hazards. These gases were produced by the burning honeycomb composite panels which comprise the ceiling, stowage bins, and hatrack. The somewhat similar shape of the curves is a clue that the two gases emanated from the same source. Moreover, a past study of thermal degradation products from aircraft materials indicated that HF and HCl, the latter in higher yields, are produced by some panels (reference 27). The source of HF was the 3-Mil Tedlar polyvinylfluoride decorative film which covers the panels. The source of HCl is probably the flame retardants used in the epoxy resin which impregnates the fiber glass facings and adheres the panel components together. Another source of HCl was the polyvinylchloride (PVC) seat components (armrest covers, side panels) and those components containing chlorinated fire retardants (cushions). It appears as if the initial gas peak was caused by the rapid thermal degradation of the decorative film and fiber glass facing resulting from the intense radiant heat from the fuel fire at the beginning of the test. The second gas peak was caused by the rapid fire involvement associated with flashover of all the interior materials. The early concentrations of acid gases (e.g., 300 parts per million (ppm) and 140 ppm for HCl and HF, respectively, at 60 seconds) are considered to be significant levels. Composite panel lining materials — the source of these gases — are important potential contributors to cabin fire hazards because of their large surface area and, in many cases, vulnerable location in the upper cabin area.

Elevated temperature, smoke, and HCN were the remaining hazards detected before the onset of flashover. Flaming conditions during a postcrash cabin fire, as opposed to a smouldering fire, make the presence of high temperatures to be expected. More unexpected was the low concentration of HCN, considering that wool is used for seat upholstery and carpet, and that wool produces high yields of HCN, approximately 40 milligrams per gram (mg/g), when pyrolyzed oxidatively (reference 27). A number of explanations for the low HCN concentrations are plausible, including (1) burning of the HCN during flashover, (2) because of the prominence of flaming, production of nitrogen oxides by the wool rather than HCN (reference 28), or (3) insufficient fire involvement of the wool due to relatively low loading and to location in the lower cabin. An interesting result was the late detection of smoke at approximately 100 seconds, in contrast to HF and HCl which were detected much earlier into the test.

In order to assess the relative importance of each cabin fire hazard, a hypothetical human survival model was formulated. (The structure of the model was suggested by Dr. Charles Crane at the FAA's Civil Aeromedical Institute. The authors are grateful for his important contribution to this paper.) The model computes incapacitation in a fire environment composed of a number of toxic gases and elevated temperature, each varying with time. The major assumptions were twofold: (1) the hazards are additive and (2) for the toxic gases, the classical hyperbolic relationship exists between gas concentration and time of incapacitation. Thus, based on the latter assumption, for a gas species i

$$c_i T_i = K_i$$

and

$$FED_i = \int_0^t c_i \; dt$$

where

c_i = concentration of gas species i
T_i = time-of-incapacitation
K_i = incapacitation dose of gas species i, a constant
FED_i = fractional effective dose, or the ratio of the actual dose due to gas species i to the incapacitation dose
t = time

The incapacitation dose constants, K_i, were calculated from the best available data in the literature (reference 28), and are tabulated below:

Gas Species i	K_i (ppm - minutes)
CO	24,000
CO_2	750,000
HCN	480
HF	1,140
HCl	2,400

The table reflects the relative toxicity of the gas species of interest; e.g., HCN is five times as toxic as HCl.

The effect of elevated temperature on incapacitation was taken into account by utilizing the empirically based curve fit, derived by Crane (reference 30), shown below

$$t_c = Q_o/T^{3.61}$$

where

t_c = time to thermal collapse (incapacitation), minutes
T = air temperature, degrees centigrade
Q_o = 4.1×10^8 a statistically derived proportionality constant

The above relationship is based on data from human exposure to a constant temperature. In order to apply this relationship to the more common time-dependent fire environment, the thermal history curve was divided into 1-second intervals. By considering Q_o as a heat factor related to the caloric intake that a body must absorb to produce thermal collapse, the thermal fractional effective dose, FED_T, becomes

$$FED_T = \frac{\Delta t \sum T^{3.61}}{Q_o}$$

Therefore, assuming the hazards to be additive, the fractional effective dose for the mixture, FED, becomes

$$FED = FED_T + \sum FED_i = \frac{\Delta t \sum T^{3.61}}{Q_o} + \sum \frac{\int_o^t C_i dt}{K_i}$$

The hypothetical time-of-incapacitation for the mixture is the time at which FED = 1.0.

The survival model described above is hypothetical. Its main purpose is to provide a means of predicting the time-of-incapacitation within a fire enclosure, based on measurements of elevated temperature and toxic gases concentrations which change, in some cases substantially, with time. Thus, it is a tool for reducing a fairly large number of somewhat abstract measurements into a single, cogent parameter: time-of-incapacitation, or the hypothetical time at which an individual can no longer escape from a fire environment. How well the model relates to actual escape potential is unknown and, realistically, cannot be determined. It is known that segments of the model are deficient for lack of available information. For example, no data exists on the effect of irritant gases (e.g., HCL, HF) on acute human escape potential. (FAA has sponsored new research at Southwest Research Institute to determine "the threshold concentration for escape impairment by irritant gases (HCL and acrolein, initially) using a nonhuman primate model and a relevant behavioral task that can be extrapolated to man.") Thus, the HCl and HF incapacitation doses utilized in the model are simply based upon extrapolation from threshold limit values (TLV's) for an 8-hour work environment. Confidence in the model is greater for the prediction of the <u>relative</u> escape time between tests on different material systems than on the prediction of <u>absolute</u> escape times.

The human survival model was applied to predict the survivability in the aft cabin based on the hazard measurements taken at the location plotted in figure 7. As shown in figure 8, the hypothetical survival time was 159 seconds when wide-body materials were installed in the cabin. Conversely, when no materials were installed in the cabin, corresponding to an idealistic and unrealistic completely noncombustible interior, there was no detectable loss in survivability, i.e., FED = 0 throughout the test. The slope of the survival curve with wide-body materials installed in the cabin increased drastically shortly after the flashover because of the rapid increase in hazards caused by the flashover. Until this test time, the survival curve was entirely driven by HF and HCl. As discussed earlier, the incapacitation doses of these irritant gases are unknown and the values used in the survival model are calculated estimates. If one ignores the hazards of HF and HCl, the survival curve becomes driven primarily by temperature and, to a lesser degree, CO. Also, the fractional effective dose will not increase above zero until 135 seconds, and will exhibit a much steeper slope than when the irritant gases are included. Four of the six hazards considered in the model eventually exceeded their incapacitation dose, as follows: temperature at 180 seconds, HF at 210 seconds, CO at 237 seconds, and HCl at 248 seconds. The fractional effective doses of the remaining hazards, CO_2 and HCN, were comparatively insignificant (0.2 and 0.04 at 240 seconds, respectively).

It has long been recognized that a margin of safety exists near the floor inside an enclosure fire. The wisdom of this advice was examined by measuring the major hazards at three elevations at test station 650 and calculating the survival time at each elevation. These survival curves are plotted in figure 9(a) and verify that survivability is possible for a longer period, the closer one is to the floor. A 34-second improvement was calculated between 5 feet 6 inches and 3 feet 6 inches, but the improvement was only 9 seconds between 3 feet 6 inches and 1 foot 6 inches. In figure 9(b) the relative importance of each hazard at the calculated survival time is graphed. The irritant gases HF and HCl again drove the survivability calculation at all three elevations. Although a contributing factor at 5 feet 6 inches, heat (elevated temperature) became negligible at the two lower elevations. Instead, CO was found to be a more important factor although this is not adequately shown in figure 9(b). This is more apparent when the survivability calculation is extended beyond the survival time; within several minutes CO will become the dominant hazard at the two lower elevations. Thus, if it is assumed that the HCl and HF incapacitation doses utilized in the model are low, and, if they are raised (i.e., the incapacitating effect of these irritant gases is made less potent in the model), then CO will be the dominant factor affecting incapacitation. Also, since CO is a more lethal agent than either HF or HCl, it may be argued that CO would be primarily responsible for any fatalaties caused by inhalation of gases near the floor. It may also then be argued that a plausible scenario for demise of an individual during a cabin fire is incapacitation, while standing, from exposure to irritant gases and heat, and, after collapsing to the floor, death from CO asphyxiation.

The most striking feature of a cabin fire is the smoke layer which because of buoyancy appears to cling to the ceiling. Figure 10 is a graph of the vertical temperature profile at various test times at test station 270, which was the first thermocouple pole station aft of the last seat row. The inflection point in the temperature profile defines the smoke layer thickness. Figure 10 illustrates that the cabin environment may be approximately described by two zones — a hot zone at the ceiling, which thickens as the fire progresses, with a linear temperature profile, and a much cooler zone in the lower cabin with a uniform, but above ambient, temperature. The temperature differential between the ceiling and lower cabin was very large; e.g., at 2-1/2 minutes the differential was higher than 1000° F. This finding has a bearing on the relevance of small-scale tests (ceiling materials are exposed to higher convective heat fluxes than are carpets, for instance).

The existence of a hot zone also has a bearing on evacuation. For example, at a station only 12 feet aft of the fire (figure 10), conditions would be clearly survivable from convective thermal exposure, as late as 2 minutes (10 to 15 seconds before flashover), for an individual who crouches in order to avoid exposure to the hot smoke layer. Moreover, a hot, smoky layer can nullify the benefit of ceiling-mounted emergency lighting, possibly by causing thermal failure in the units, or by obscuring exit signs or blocking illumination.

The existence of large heat losses into the walls of an enclosure during a fire and the entrainment of lower zone cool air into the hot smoke layer creates corresponding losses in the heat content, or temperature, of the smoke layer gases as they are transported away from the fire origin. Figure 11 is a graph of the symmetry plane air temperature at the ceiling throughout the cabin at various times into the test. Because of the aforementioned heat losses, the ceiling temperature decreased significantly with distance away from the fire. Although measurements near the fire were off-scale at 1800° F after 2-1/2 to 3 minutes into the test, because the thermocouples were not shielded from radiation these readings may be higher than the actual air temperature. The temperature profile at 2 minutes indicates that a large area of the ceiling was subjected to temperatures in excess of the thermal decomposition temperature of the composite panels, approximately 200 to 350 degrees centigrade (°C), before the occurrence of flashover (reference 31). Examination of figure 11 illustrates that the galley partition tended to confine much of the heat to the cabin section forward of the partition. A related observation has been made in accident aircraft where fire damage was more extensive on the fire origin side of a class divider than on the protected side. It is of interest to note that the ceiling temperature aft of the galley partition is more uniform than the ceiling temperature in the forward cabin. This apparent uniformity may have resulted from more active mixing in the smoke layer caused by the partition openings and by entrainment of fresh air through the exhaust door.

EVALUATION OF SEAT CUSHION FIRE BLOCKING LAYERS

The C-133 test article was utilized to evaluate the effectiveness of aircraft seat cushion fire-blocking layer materials. This work was undertaken in response to the SAFER Advisory Committee recommendation pertaining to cushioning fire blocking layers (reference 19). Because of the high work priority, general interest in these materials and lack of data under postcrash fire exposure, the evaluation was performed under both large- and full-scale conditions to assure highest confidence in the test results.

This paper will be limited to the initial work on foam blocking layers (Vonar and LS-200) to demonstrate the effectiveness of the concept. More recently, aluminized fabrics such as Preox™ and Norfab™ have exhibited promising fireblocking characteristics at less weight than the foams. Both blocking layer systems will be discussed in a separate comprehensive final report.

The fire blocking layer materials were evaluated at a number of seating configurations and test conditions, each with a specific objective. The bulk of the tests were performed on single or multiple seats exposed to the fuel fire at the fuselage opening without any other interior materials installed in the cabin. The first series of tests were on double seat cushions supported by a metal frame. In this manner, performance benefits provided by blocking layers could be determined without contributions and possible confusion from the fire involvement of other materials. Subsequent tests were performed on real seats to examine the benefit in the context of remaining seating materials. Multiple seats were evaluated to study the effect of blocking layers on seat-to-seat fire growth. In order to examine the effect of the primary test configuration (76-inch by 42-inch opening, seat adjacent to opening), a series of tests were run with a smaller opening (2-foot square), and another series treating the opening as a doorway (with appropriate rearrangement of seating). Finally, tests were performed with a section of the cabin completely installed with interior materials in order to determine fire-blocking layer benefits under the most realistic conditions achievable.

The forward cabin temperature history is plotted in figure 2 for the initial test series on cushioning mounted on a double seat, metal frame. In this test, as throughout the program, the seat upholstery fabric was a wool (90 percent)/nylon (10 percent) blend. The results were very encouraging in that each concept exhibited a significant improvement over the baseline cushion, FR urethane. Two Vonar types, each 3/16-inch thick, were evaluated — polyester (PE) scrim and fiber glass (FG) scrim. Both Vonar materials produced results similar to the LS-200 full cushion, which is considered to be the premium flexible foam cushion in terms of fire safety. The Vonar results were considerably better than the results with LS-200 as a blocking layer (at double the thickness of Vonar). The superiority in fire performance of seat cushions protected with Vonar, as compared to unprotected cushions, was consistently demonstrated throughout the program for each of the aforementioned series of tests.

What is the safety benefit of seat cushion fire blocking layers during a postcrash cabin fire within the context of the remaining interior materials? This question was answered by performing a test with a section of the C-133 test article completely lined and furnished with interior materials (see figure 5), and with the FR urethane cushions encased in Vonar PE blocking layers. The difference in survivability between the full-scale test with Vonar and the full-scale test with unprotected cushions was the safety benefit. Figure 13 is a graph of the calculated fractional effective dose history for each of these tests. The calculation does not include the effect of HCl in any of the tests because of a malfunction in the analysis of HCl in the test with Vonar. The calculated safety benefit provided by Vonar was 60 seconds for the particular fire scenario that was simulated. In order to compare the performance of Vonar protected cushions with the ultimate protection — noncombustible cushions — a full-scale test was conducted with the seat upholstery covers stuffed with Kaowool", a ceramic fibrous insulation. Surprisingly, the increase in safety provided by the noncombustible cushions over that provided by the Vonar protected cushions was only 8 seconds. This comparison indicated that the fire protection offered by Vonar was nearly equivalent to a noncombustible cushion. Thus, if not a practical solution in itself, Vonar, by its excellent performance in full-scale fire tests, provided a lofty and achievable fire performance goal for seat cushion blocking layer materials under consideration for aircraft usage. Figure 13 also indicates that, in the test conducted with a noncombustible interior, there was no detectable detriment to survival. Thus, major potential improvements in cabin fire safety may exist, beyond that provided by seat cushion blocking layers, from an upgrading of the fire performance of the remainder of the cabin interior (e.g., ceiling panels, stowage bins, etc.). Whether there exists materials with enhanced fire performance, as well as acceptable functionality, durability, processability and weight, remains to be determined.

Smoke was not a component of the human survival model discussed previously in this paper. Aside from possible physiological and psychological effects which are presently beyond mathematical description, the major impact of smoke is to obscure visibility and, thereby, increase the time required to evacuate an airplane. Thus, the net effect from the existence of dense smoke will be prolonged exposure of cabin occupants to fire hazards, which may ultimately cause incapacitation of some occupants before they are able to escape. The loss in visibility in the aft cabin was calculated and plotted in figure 14 for the previously discussed full-scale tests. The following simple equation derived by Jin (reference 32) was employed to compute visibility from the light transmissivity measurements:

$$D/L \times V = 3.5$$

where

D = optical density ($D = \log \frac{1}{T}$, T is fraction of light transmitted)

L = light transmissometer path length

V = visibility of a backlighted sign

The most striking feature of the curves in figure 14 is the rapidity by which visibility became obscured; e.g., in some cases visibility was reduced from the length of the cabin to less than the width of the cabin in approximately 15 seconds. Also, by comparing figures 13 and 14, it is apparent that smoke became an important factor well before survival was no longer theoretically possible. For example, visibility was reduced to less than the width of the test article at 30 to 60 seconds before the hypothetical survival time for each of the three full-scale tests with interior materials. The ranking of results for visibility (figure 14) was identical to the rankings for hypothetical survival time (figure 13), although the time increments between the curves were not equal. For example, the application of Vonar to aircraft seats increased the hypothetical survival time by 60 seconds (figure 13), whereas the improvement in visibility from reduced smoke levels was 48 seconds (when visibility was reduced to the cabin width).

SUMMARY OF SIGNIFICANT FINDINGS

Based on the full-scale tests and analysis described in this paper, which examined the cabin fire hazards arising from an external fuel adjacent to a large fuselage opening in an intact fuselage, with minimal fuel-fire flame penetration but intense radiation into the cabin, the following are the significant findings:

(1) Burning cabin interior materials can be the primary factor affecting occupant survivability in certain types of postcrash fires despite the presence of a large fuel fire.

(2) Uncontrolled postcrash fires in an intact fuselage will produce a flashover condition, which will be followed by a loss in survivability throughout the cabin.

(3) The only fire hazards of significance measured before the onset of flashover were the irritant gases, HF and HCl, and smoke produced by burning composite panels and, possibly, seats.

(4) In tests with zero wind and the cabin interior realistically furnished and lined with interior materials, application of a Vonar fire-blocking layer on seat cushions improved the calculated survival time in the aft cabin by 60 seconds.

(5) Potential benefits to cabin fire safety beyond those provided by seat cushion blocking layers may be realized from improvements made to the remaining interior materials; however, it is presently unclear if effective and practical alternate materials are available.

ADDITIONAL WORK

There are a number of planned projects with the C-133 test article, which are continuations of the initial work described in this paper, with the overall goal to better understand and characterize the role of cabin interior materials in postcrash cabin fire survivability. Examination of the effect of fire scenario and material application (e.g., ceiling paneling, sidewalls, carpeting, etc.) on cabin fire hazard development is planned. Also, advanced interior materials to be developed and identified by the National Aeronautics and Space Administration (NASA) will be tested in a realistic manner to determine if significant improvements in survivability can be realized. Finally, the C-133 test article will be utilized in a study designed to determine which small-scale test results give the best correlation with the hazards of burning interior materials during a postcrash cabin fire.

A considerable amount of work has been performed on seat cushion blocking layers beyond that described in this paper. Tests by the FAA have demonstrated that potentially destructive in-flight and ramp fires can be prevented by the application of cushion blocking layers. Because the weight penalty of Vonar PE appears excessive, approximately 2-3 pounds per seat, FAA has entered into an interagency agreement with NASA to develop effective lower weight blocking layer materials. An important finding under this agreement is the apparent effectiveness of aluminized fabrics encasing untreated urethane cushions, resulting in minimal, if any, weight penalty. FAA plans to evaluate this configuration under full-scale postcrash fire conditions in the C-133 test article. Tests completed by the FAA have demonstrated that untreated urethane cushions encased in an aluminized fabric are superior to unlayered FR urethane cushions when subjected to small ignition sources. Other efforts under the interagency agreement include development of a cost/weight computer program, evaluation of the durability of candidate blocking layer materials and large- and small-scale fire tests on candidate materials. Finally, FAA, NASA, Boeing, Lockheed, and McDonnell Douglas are participating in a round-robin evaluation of their respective small-scale fire test methods for seat cushion blocking layers. Eleven material configurations are being evaluated in the round-robin test series as well as under large-scale fire test conditions.

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ACKNOWLEDGEMENTS

The authors are grateful to the following individuals who made important contributions to this paper. Dr. Charles Crane of the FAA's Civil Aeromedical Institute suggested the formulation of the human survival model. Mr. Louis Brown of the FAA Technical Center directed the preparation and conduct of the C-133 fire tests, and Ms. Louise Speitel and Mr. Robert Filipczak, also of the Technical Center devised and performed the difficult sampling and quantitative analysis of irritant and organic gases. Graphs and figures were skillfully prepared by Mr. George Johnson.

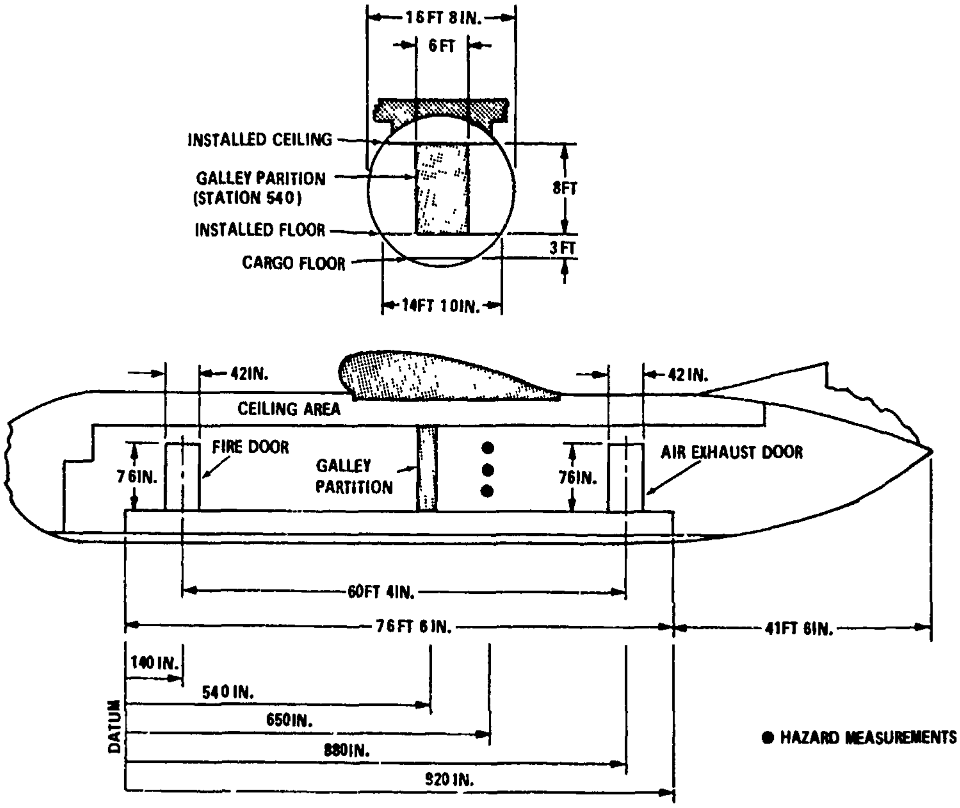


FIGURE 1. SCHEMATIC OF C-133 WIDE BODY CABIN FIRE TEST ARTICLE

FIGURE 2. FULL-SCALE FIRE TEST FACILITY

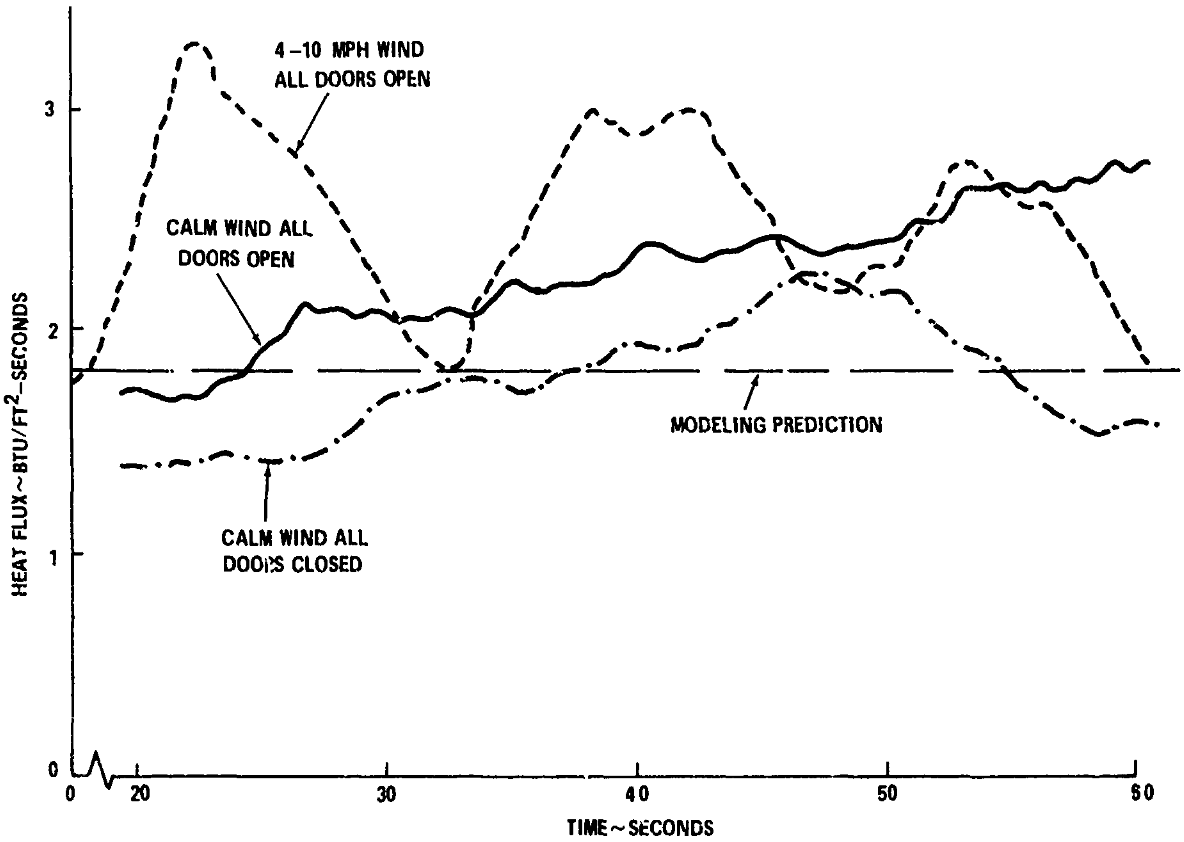


FIGURE 3 DC7 SYMMETRY PLANE HEAT FLUX

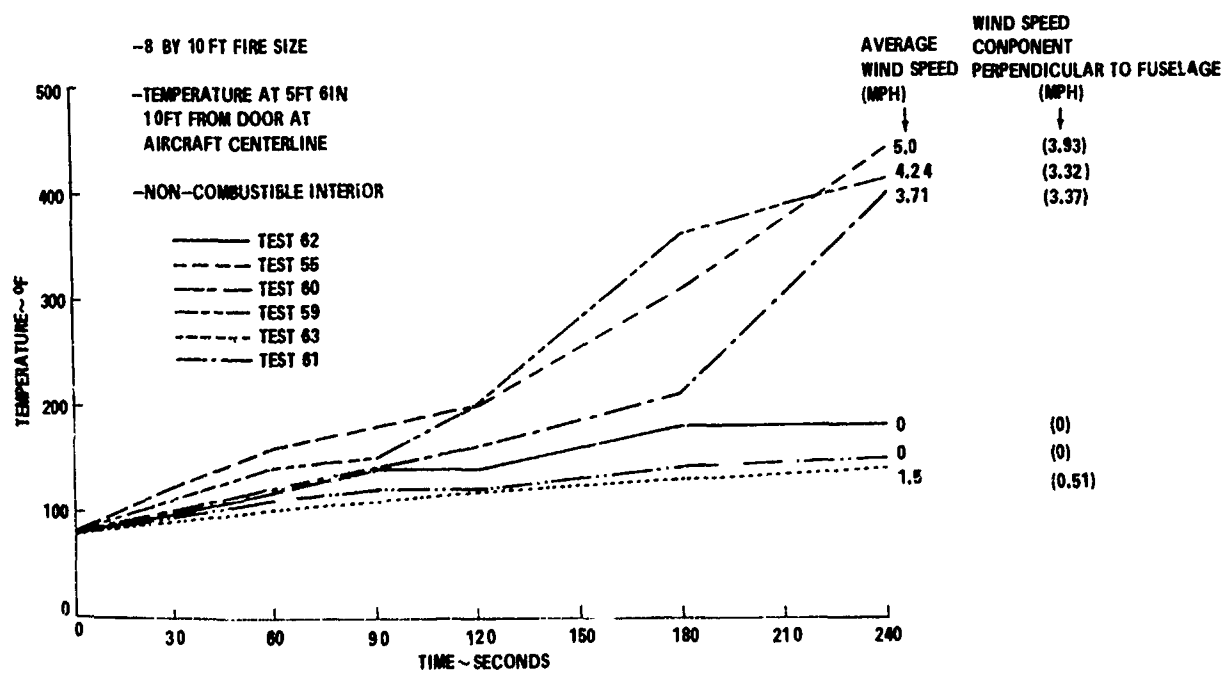


FIGURE 4. EFFECT OF WIND SPEED ON CABIN TEMPERATURE WITH FUSELAGE DOWNWIND OF FIRE

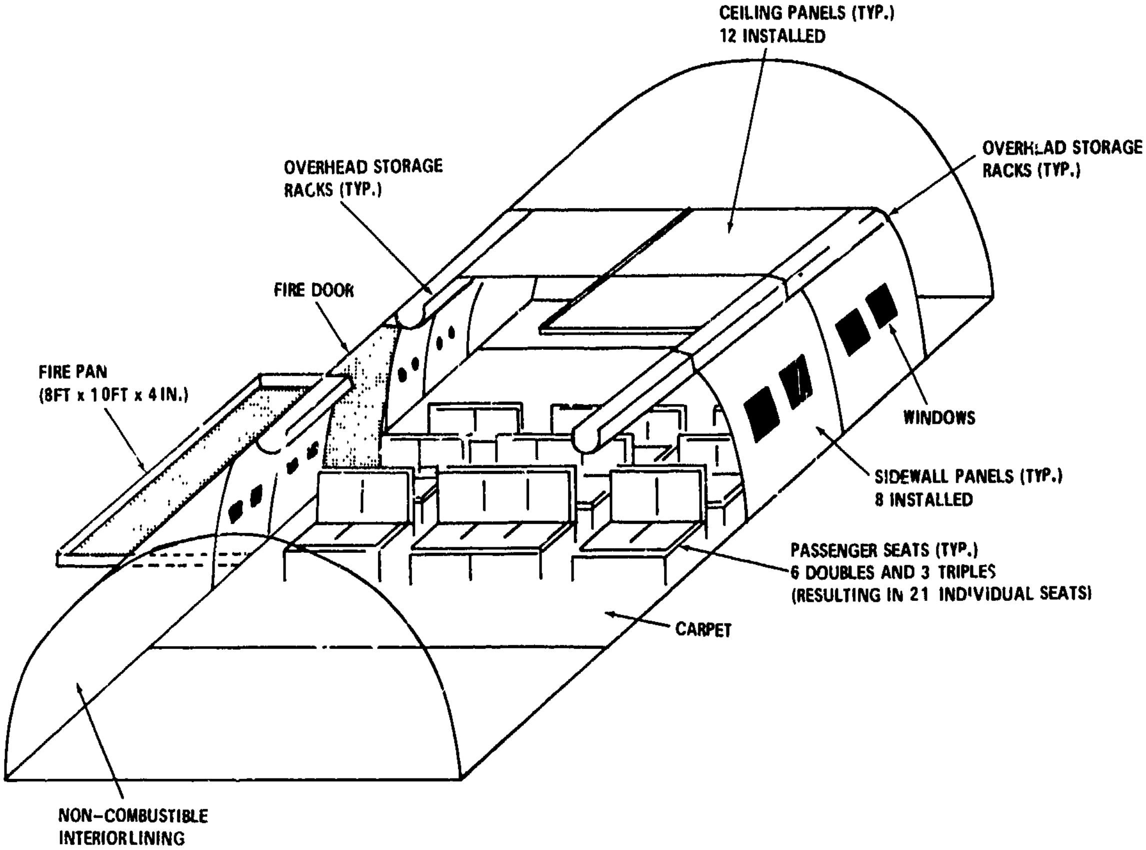
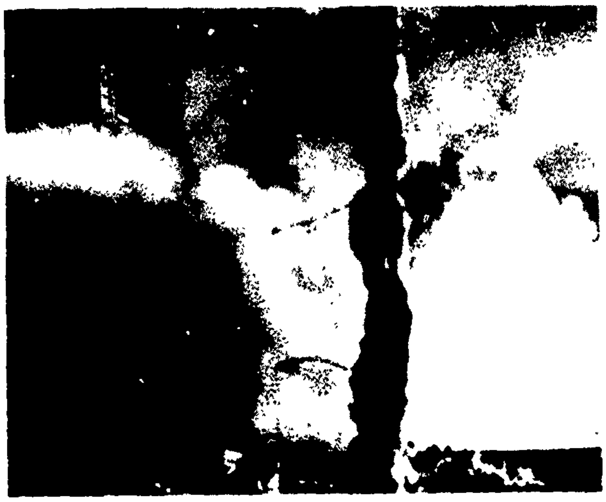


FIGURE 5. INSTALLATION OF WIDE BODY MATERIALS INSIDE C-133 TEST ARTICLE

(a) 2:05



(b) 2:10

(c) 2:15

FIGURE 6. PHOTOGRAPHIC DOCUMENTATION OF FLASHOVER

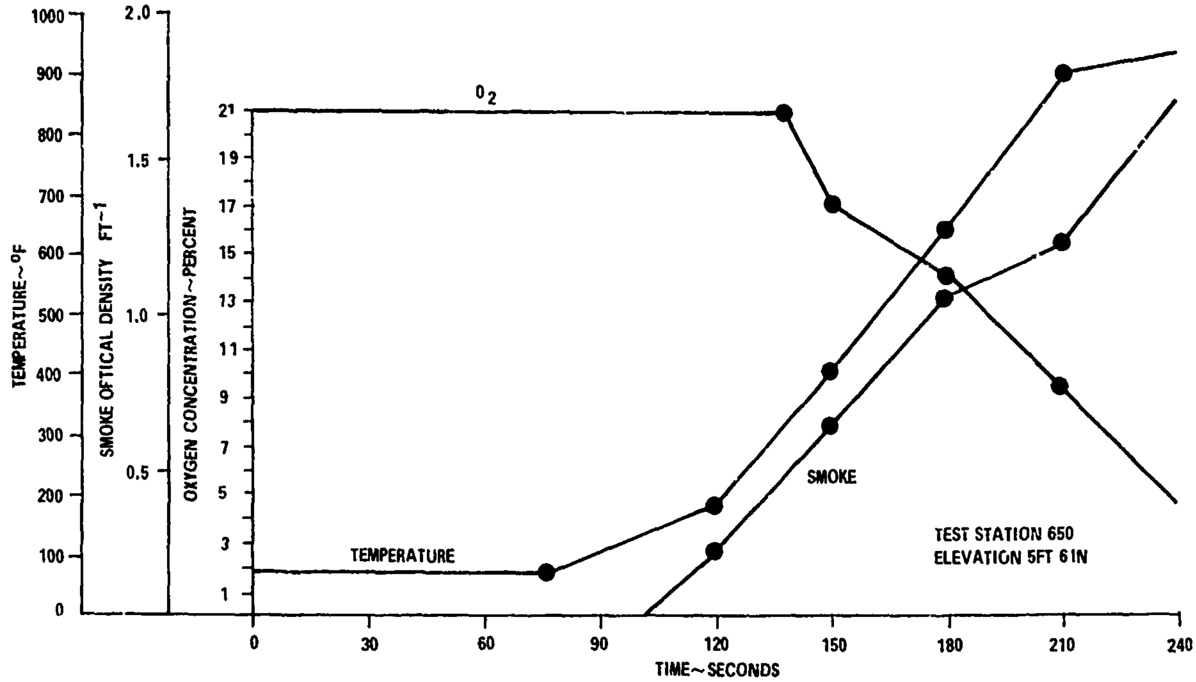
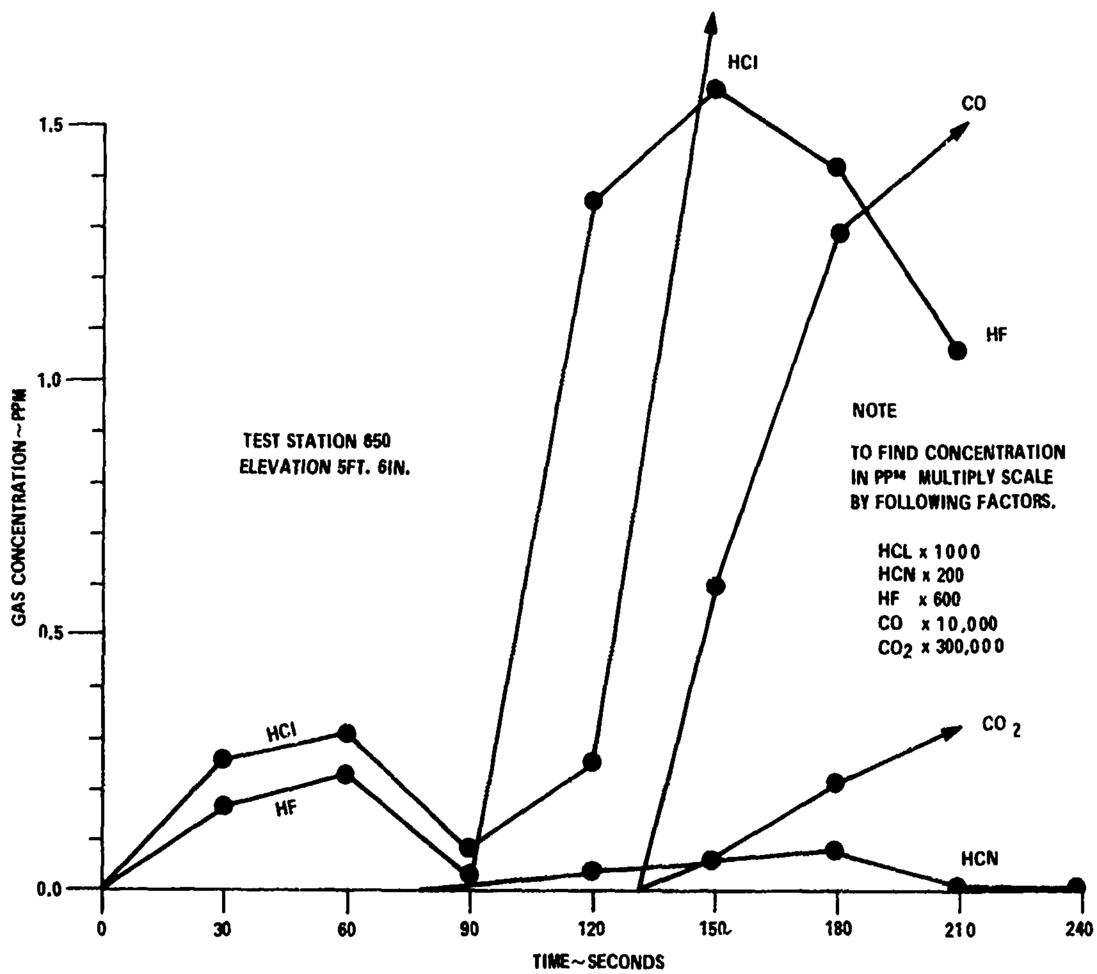


FIGURE 7(a). HAZARDS IN AFT CABIN PRODUCED BY BURNING INTERIOR MATERIALS



FIUGRE 7(b). HAZARDS IN AFT CABIN PRODUCED BY BURNING INTERIOR MATERIALS

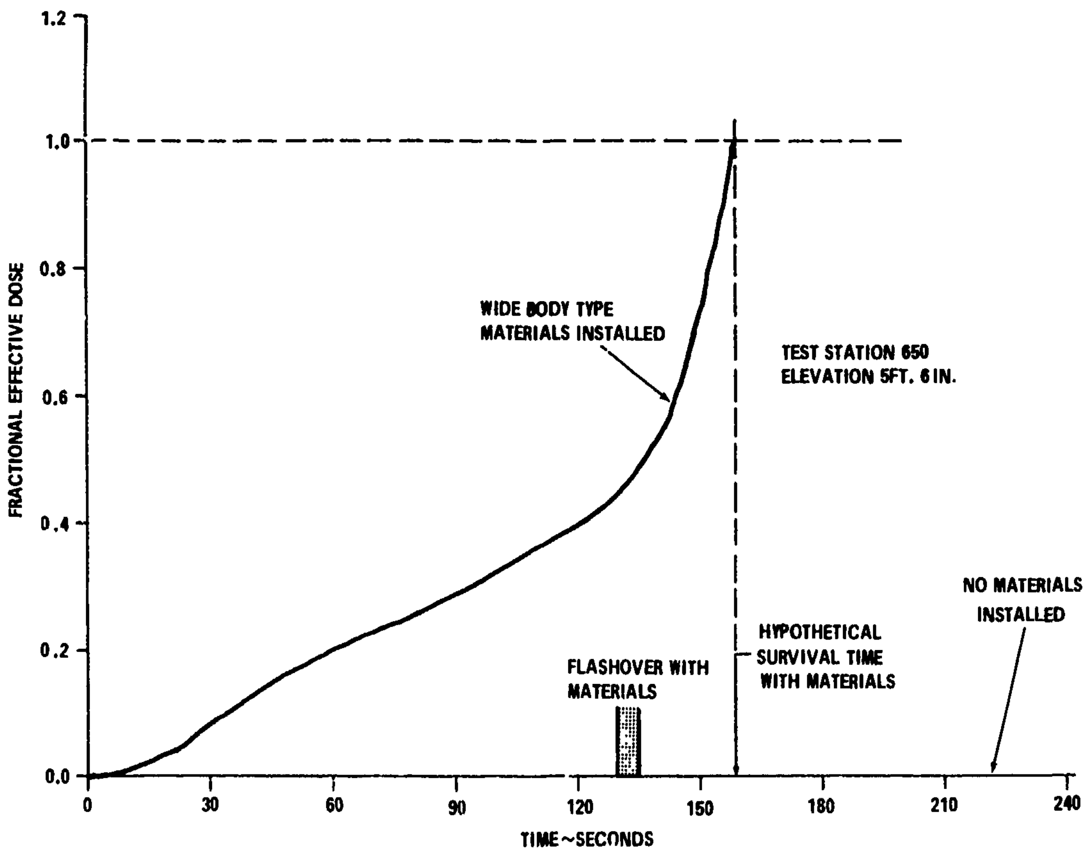


FIGURE 8. HYPOTHETICAL SURVIVAL CURVE IN AFT CABIN

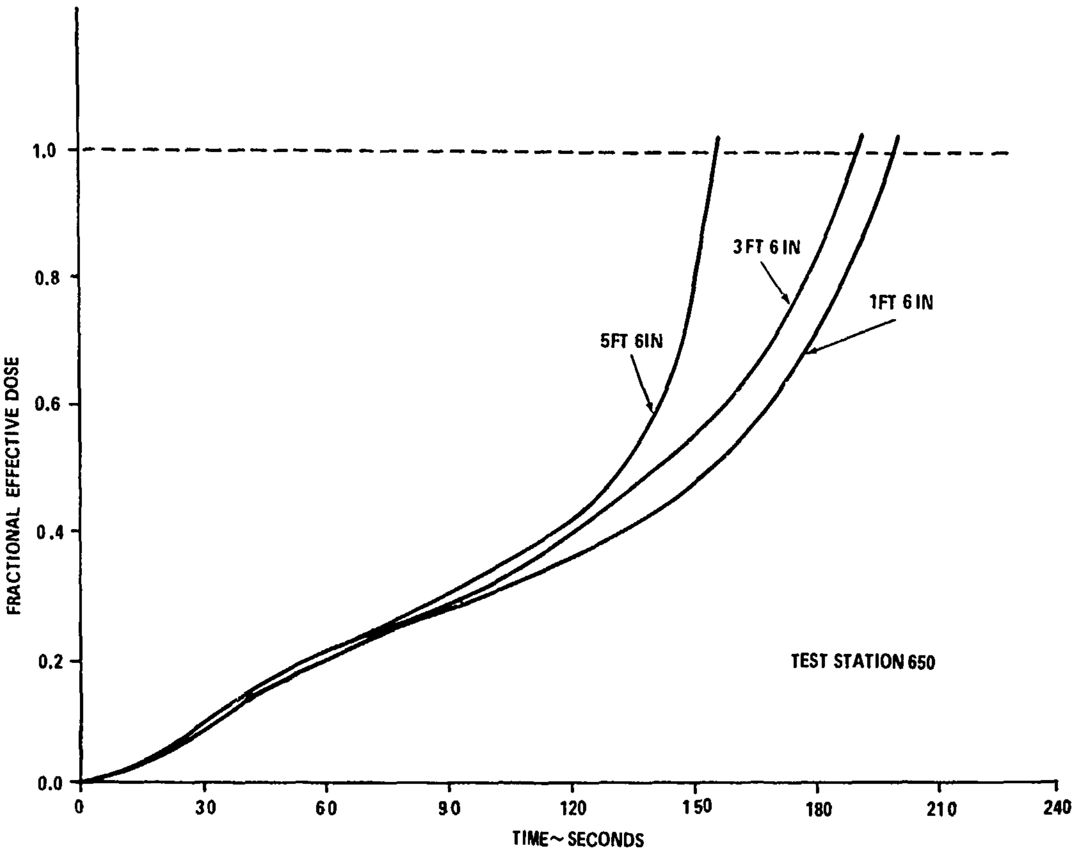


FIGURE 9(a). EFFECT OF ELEVATION ON SURVIVABILITY IN AFT CABIN

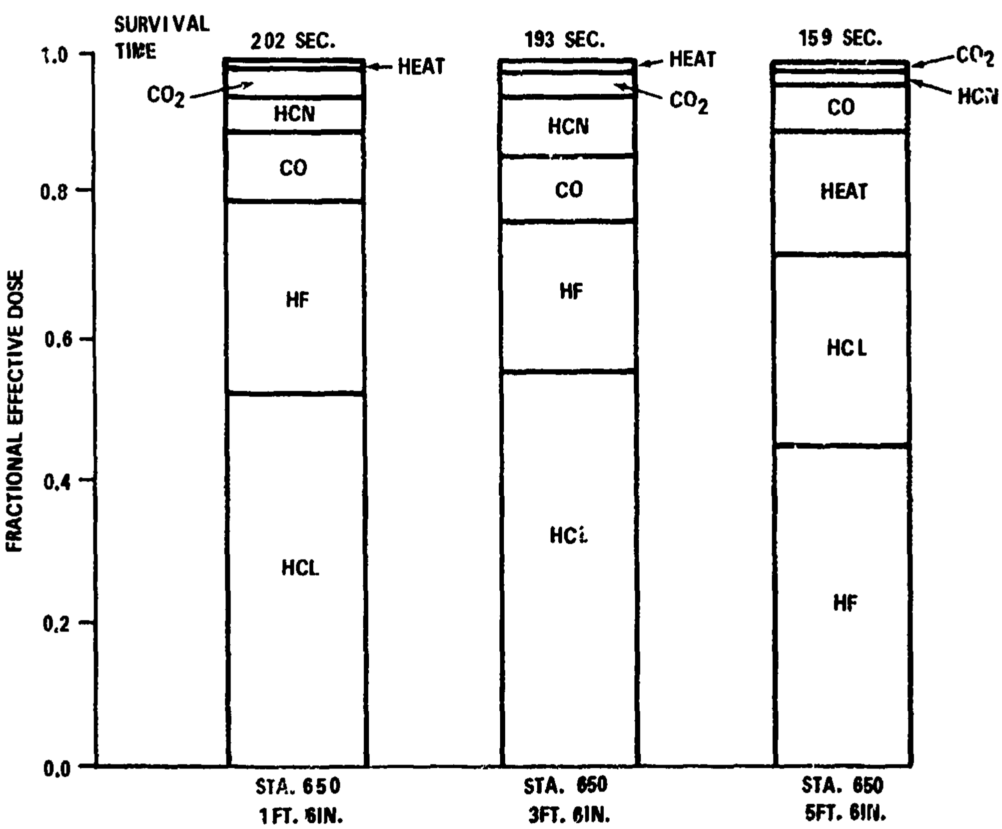


FIGURE 9(b). EFFECT OF ELEVATION ON SURVIVABILITY IN AFT CABIN

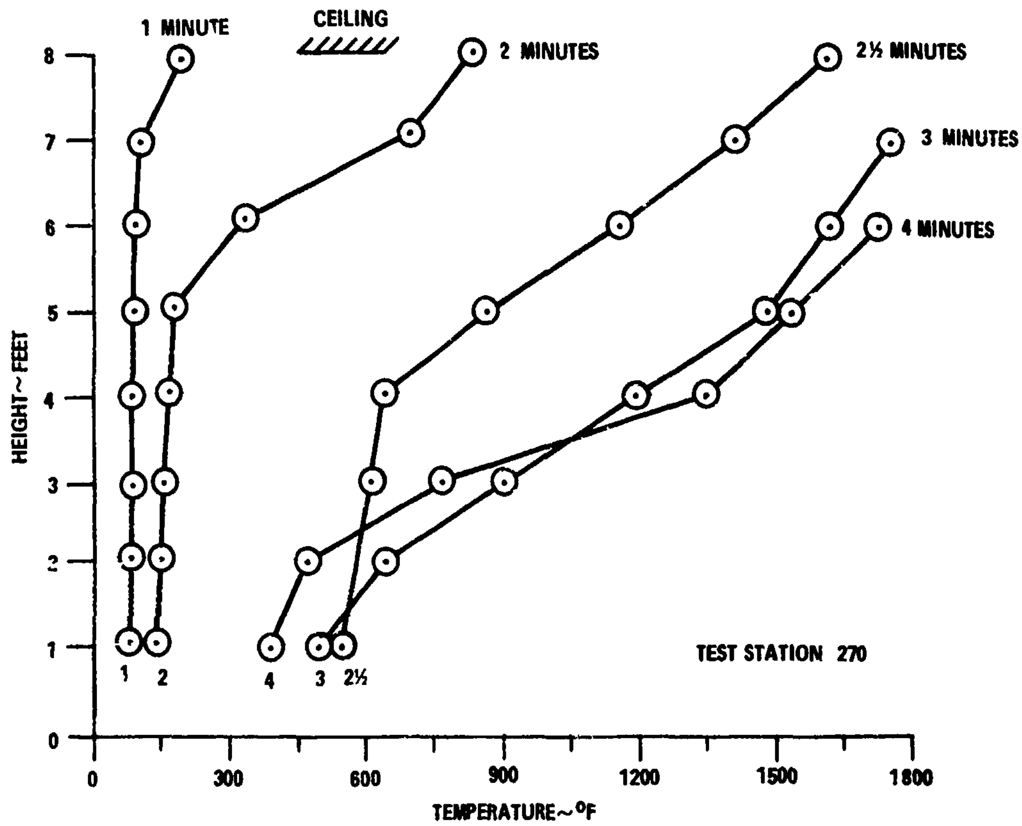


FIGURE 10. HEAT STRATIFICATION IN FORWARD CABIN

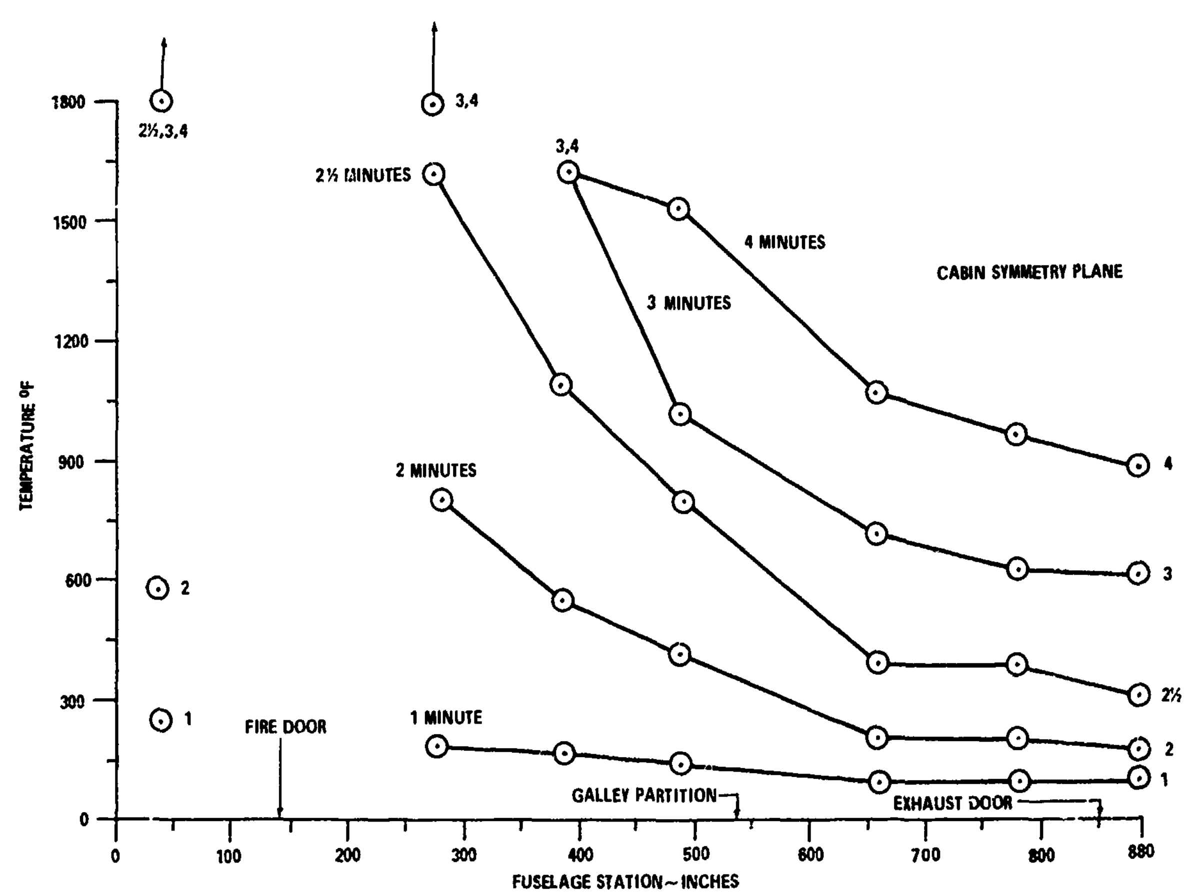


FIGURE 11. LONGITUDINAL TEMPERATURE PROFILE AT CEILING

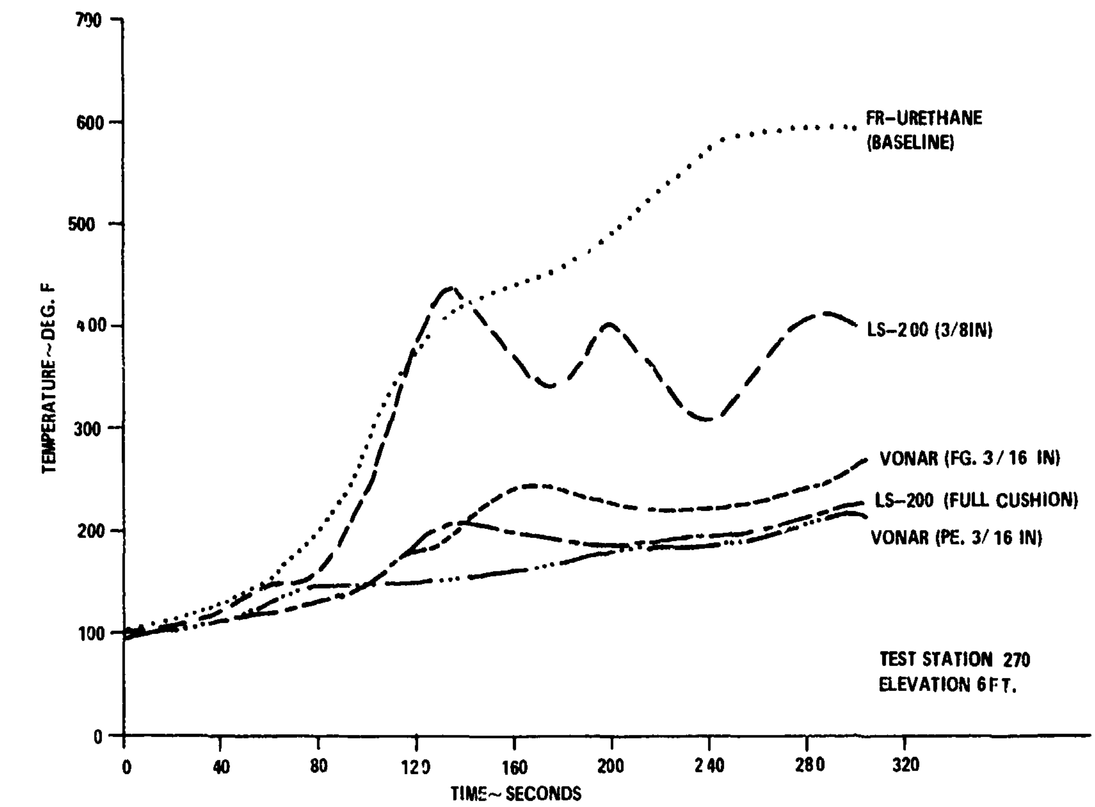


FIGURE 12. BLOCKING LAYER RESULTS ON DOUBLE SEAT CUSHIONING MOUNTED ON METAL FRAME

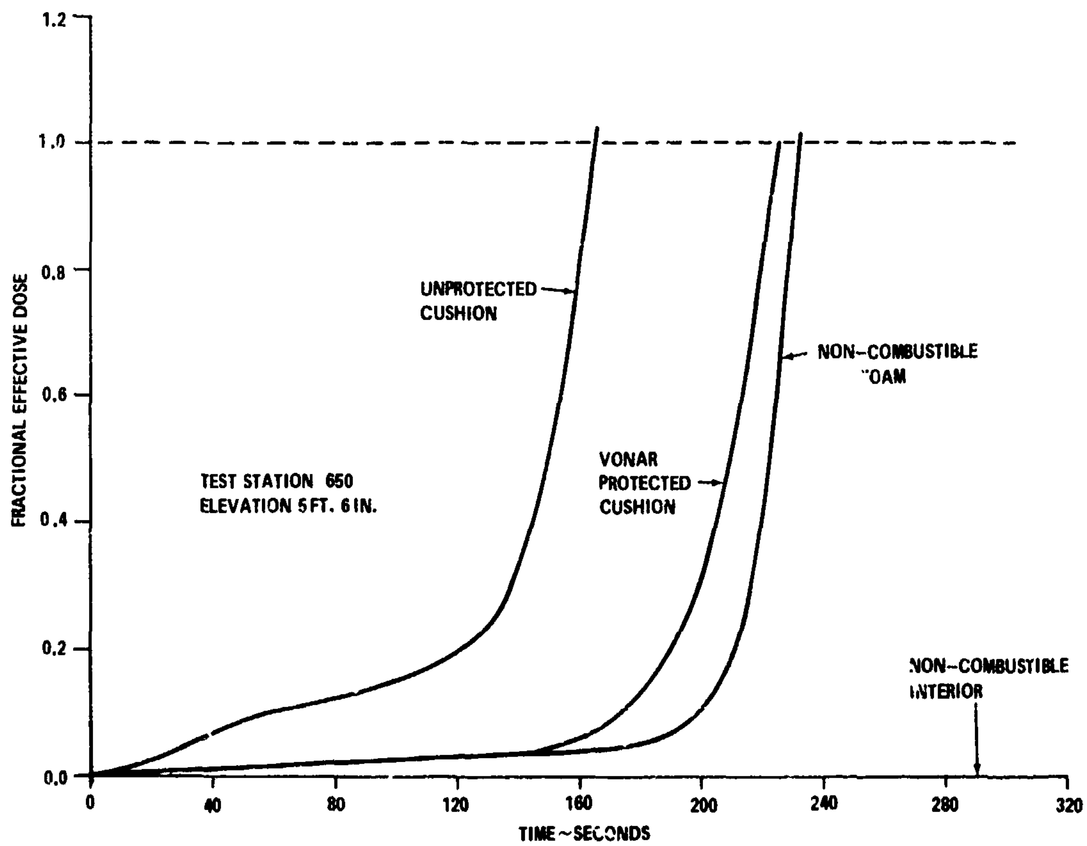


FIGURE 13. EFFECT OF CUSHIONING PROTECTION AND MATERIALS ON CALCULATED SURVIVAL TIME

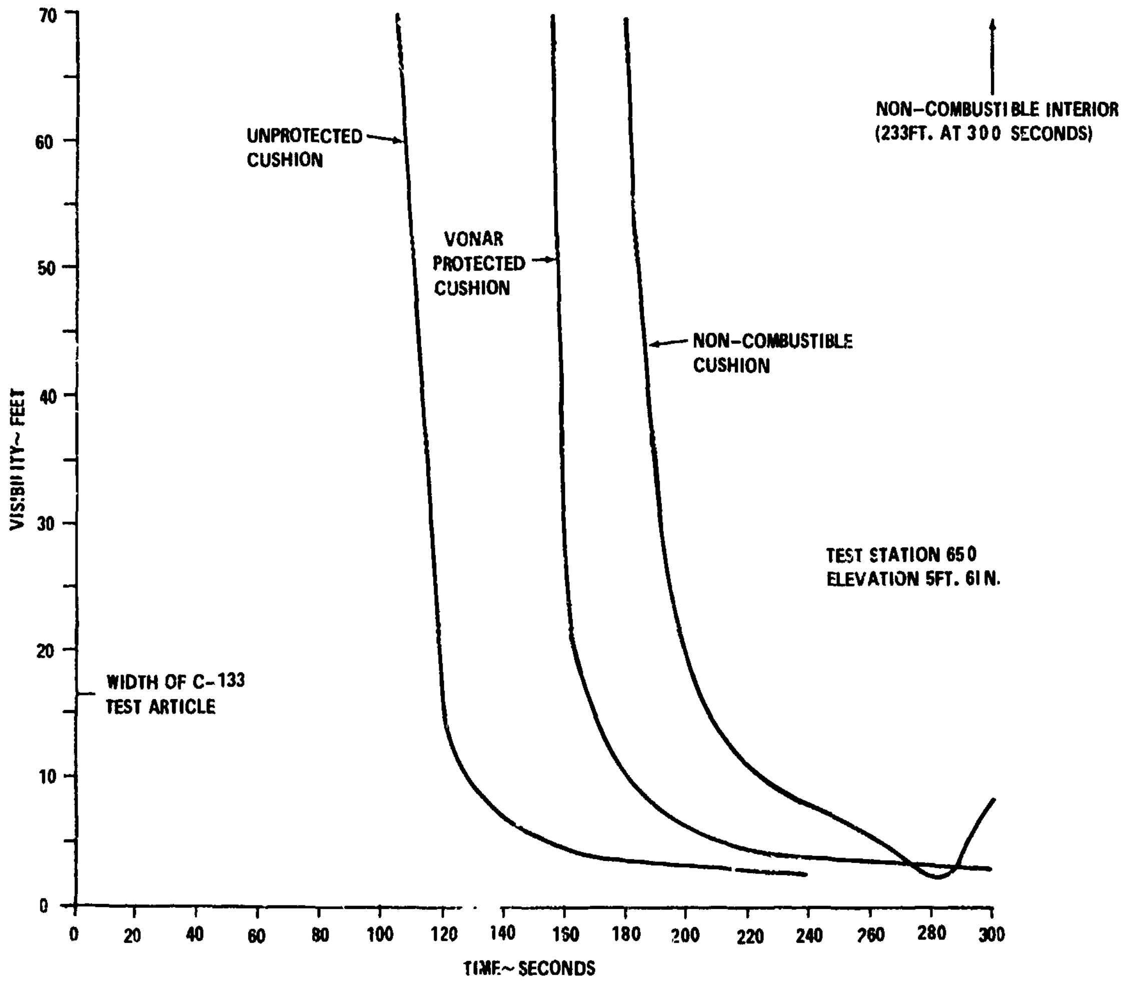


FIGURE 14. EFFECT OF CUSHIONING PROTECTION AND MATERIALS ON CALCULATED VISIBILITY THROUGH SMOKE

AIRCRAFT POST CRASH FIRE REDUCTION/SURVIVABILITY ENHANCEMENT FROM A MANUFACTURER'S VIEWPOINT

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SUMMARY

In reviewing this subject the author emphasises the importance of achieving a balanced level of overall safety for both flight and crash situations. Comment is made on past and current R & D both in the area of external fire effects and occupant escape.

As an example of the Constructors' approach to crashworthiness the requirements developed for the SST are outlined together with chosen examples of the means of compliance.

The complex problem of cabin interior material combustion hazards is discussed and a detailed account is given of visibility tests in a smoke-filled cabin including an assessment of the relative importance of toxicity effects in hindering escape.

NOMENCLATURE

A	Material surface area ft^2
C	Gas concentration ppm
D	Optical density
Ds	Specific optical density of a material
e	Exponential
F	Transmitted light flux (i.e. light received after passing through a medium)
Fo	Incident light flux (i.e. light output from a source into a medium)
L	Light path length through medium ft
T	Percentage of light transmitted through a distance L of a medium %
V	Combustion chamber volume ft^3
σ	Photometric attenuation coefficient of a medium

SUFFIXES:-

c	Cabin
t	Test cell (i.e. N.B.S. Smoke Chamber)
'	Value related to limiting visibility conditions

1. INTRODUCTION

The design of civil transport aircraft and the various aspects of safety is largely governed by internationally recognised Airworthiness Regulations imposed by various Certificating Authorities. In addition to the achievement of these high established standards any new design of aircraft is carefully reviewed by the Airworthiness Authorities in collaboration with the manufacturer to ensure that all practical and justifiable measures have been taken in the interests of safety. Recognition that these objectives were satisfied in respect of aircraft currently in service is reflected in the Certificates of Airworthiness held for these aircraft.

2. AIRWORTHINESS AND CRASHWORTHINESS

Those who are concerned with aviation safety will appreciate the importance of the aircraft constructors' desire to achieve a nigh standard of "overall safety", but bearing in mind that the major period of passenger occupation of the aircraft is spent in the air it will not be surprising to learn that the constructors' prime concern has been to minimise in-flight incidents and their potential consequences. It is important to recall that there are numerous aspects of in-flight fire safety already included in the Airworthiness Regulations which must be satisfied by the Constructor. When these are compounded with other requirements to minimise post-crash fire occurrences, plus the provision of easy access to systems for aircraft maintenance, or ensuring that the weight penalties and cost are kept realistic, then it becomes obvious that many objectives must give way to some degree of compromise without impairing the basic safety objectives.

This optimisation of an aircraft design requires considerable foresight at the projecting stage since no amount of struggling thereafter can totally rectify matters of fundamental configuration without incurring enormous cost and serious delay to design programmes. It is therefore important that the various specialist disciplines are properly co-ordinated if the optimum level of overall safety is to be realised. Unfortunately, the discipline of Fire Engineering is far from being a pure science and, of necessity, one has had to lean heavily on accumulated experience of past accidents, the interpretation of results from research, and the application of engineering judgements.

Due to the variety of possible aircraft configurations each one will exhibit certain advantages or disavantages over another in respect of in-flight fire safety and crash-worthiness. For example, some aircraft have their engines mounted in pods on the rear part of the fuselage as opposed to on the main wing. Apart from the obvious aerodynamic advantages of leaving the flying surfaces aerodynamically clean the following safety advantages were claimed:-

a) Engine fires, which are by far the most frequent occurrence, would not result in flames passing over the wing structure to either weaken it or cause hot surface ignition of the fuel in the tanks. Neither would they pass over a high mounted tailplane.

b) Projectiles from uncontained mechanical failures of the engine would not puncture the wing tanks and release an unchecked loss of fuel or cause possible ignition. This consideration is relevant to ground operations of the aircraft as well as in-flight.

c) Projectiles from uncontained engine failures would not puncture the pressure cabin or injure passengers. Again, a possible ground situation.

d) In crash situations of moderate severity the engines, being mounted high up on the side of the fuselage, would not easily be wiped off or damaged such as to release flammable fluids in the immediate area of very hot surfaces. However, on the other hand, these engines being at the rear might more readily ingest kerosene spilled from wing tanks in more severe crash cases.

Similarly, it might be argued that a high wing aircraft is more likely to escape wing tank damage than a low wing aircraft in a crash of moderate severity.

Of course, there are counter arguments to support other configurations and they are not necessarily dictated by crash considerations.

Apart from the consideration given to the location of engines in relationship to fuel tanks, potentially destructive energies are also stored in such items as under-carriages. These have featured, in their own right, in many accidents. Undercarriages have been described as a necessary evil. They are certainly massive items to stow away inside the airframe considering the premium of space available. The duty cycle is short, but it is severe and is perfromed at critical stages of aircraft operation.

Several failure cases have to be considered, for example, the burst tyre with the gear extended. This results in a sudden release of pressure energy which alone is capable of causing severe deformation and damage to structure in the immediate area. Associated with this type of failure there is the possible release of part of the tread, or even the whole tread, which can unwind and whiplash whatever lies in its path. It is therefore essential to ensure that flammable fluid pipes and electrical wiring are not exposed to this risk of damage and possible fire with passengers on board the aircraft.

Although wheel rotation is stopped by the time the gear is stowed, and notwithstanding the fact that protection is afforded by fusible plugs in the wheel rim, the potential consequences of a tyre-burst in the stowed position also receives very careful consider-ation.

3. POST-CRASH FIRE SURVEYS

What is a post-crash fire? There is no single answer to this question, but intensive studies of accident data have been conducted with a view to identifying any common factors and to determine whether these might possibly be eliminated by practical and cost-effective design action. Whilst many accidents have clearly demonstrated the value of the crash-fire prevention design features already incorporated on aircraft, as is required by the airworthiness regulations, it is also clear that it is impossible to design for every eventuality. Due to the lack of adequate information and the extreme complexity of the post-crash fire environment many of the past surveys of accidents failed to define the problem in terms that would permit meaningful regulatory action to be taken. However, these surveys have been very worthwhile in helping to direct the course of research and development from which we will gain a better understanding. In this regard the two most informative references available to industry at the present time are the Final Report of the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, and AGARD Advisory Report No. 132.

Faced with a multiplicity of possible post-crash fire scenarios, which are reviewed in great detail in the above two referenced documents, the aircraft constructor will continue to place primary importance on crash prevention. However, there will always be scope for minimising the risk of fire and its consequences.

4. RESEARCH AND DEVELOPMENT

Looking back over a period of thirty years of fire engineering involvement I have been very much impressed by the volume of research effort that has been directed to the fire safety problem and to the crash fire problem in particular. This dedication, backed by massive resources, has been greatly intensified in recent years. In particular, the output of data from the U.S.A. has been overwhelming and has covered passenger cabin fire situations as well as external fuel fire situations.

Not all of the past research was successful in meeting the initial hopes and in consequence did not result in the issuance of new regulations. One notable example was the research into gelled and emulsified fuels, which certainly seemed to be attacking the heart of the problem. During that period both the aircraft constructors and airworthiness authorities came under considerable pressure from certain sections of the public which did not understand the technical difficulties. Public concern is, of course, very understandable, especially following a major accident involving fire - regardless of whether it was otherwise survivable. Credit is not always given for the technological improvements that have been introduced into aircraft from time to time. Also, it is not always appreciated that the constructors' apparent resistance to the introduction of new but promising ideas stems from their insistence that exhaustive tests be carried out to ensure that the currently attained level of overall safety is not likely to be diminished.

In addition to the reviews of both current and future research contained in AGARD Advisory Report 132 and the Final Report of the SAFER Committee these two recent documents also contain detailed descriptions of the numerous fire safety measures already incorporporated in aircraft designs by the manufacturers. In so far as representatives of the civil aircraft industry participated in the activities of these committees their views on all currently suggested concepts for further post-crash fire protection have been fully recorded. These reports are also seen as significant in that they present an international consensus of expert opinion on all aspects of aircraft design and operation.

Some of the new concepts that have been proposed for research are quite clearly high risk concepts involving high costs far beyond the resources of any one manufacturer. If rapid progress is to be realised in these programmes then significant funding by governments would seem essential.

Concepts that have been suggested for post-crash fire and fuel tank explosion prevention include nitrogen inerting (both liquid and on-board gas generating systems), reticulated polyurethane foam or expanded metal foil, explosion suppression systems, crash-resistant bag tanks, and Anti-Misting Kerosene (AMK). Bag tanks are currently used in limited applications whilst the other concepts have serious disadvantages for civil aircraft or are not sufficiently developed to be acceptable. The aircraft Constructor and Airworthiness Authorities must be satisfied that the claimed safety gains are not nullified by hidden additional hazards. The Constructors endorse the conclusion expressed by the SAFER Committee that AMK technology, if successful and practicable, could provide the single most significant safety improvement to reduce the post-crash fire hazard.

5. PASSENGER EVACUATION SYSTEMS

Over the past years of aircraft operations the inflatable type escape slide has clearly demonstrated its worth in achieving rapid evacuation of aircraft occupants in emergency situations. However, they are extremely sensitive to fire, and should they be attacked by even small flames from an encroaching pool fire, they could quickly deflate when a few more vital seconds might save lives. Following actual incidents of this kind a programme of research was put in hand both in the U.K. and U.S.A. to investigate materials and protective coatings that might at least extend the survival time of the escape slide when exposed to radiant heat. Some coatings have already been developed, the priority now being to determine whether these coatings can be satisfactorily applied to slides currently in service. This approach would seem to be very necessary bearing in mind the vast number of slides that are in existence with many years of useful life still remaining.

The level of radiant heat chosen for some of these tests was 2 to 3 Watts/cm^2. This is believed to equate to the threshold of pain during a 1.5 second exposure of a person coming down the slide. Not surprising, the weakest areas of inflatable slides in the presence of flame are the adhesive bonded seams.

It must also be remembered that on some aircraft the inflatable slides are designed to be used as rafts in the event of aircraft ditching over water. Therefore, in developing heat-reflective coatings consideration is having to be given to the loss of conspicuity - the present colour being orange.

In developing any new materials and constructions for slides it is the Constructors' hope that the final bulk package will be no larger or heavier than is currently accommodated on the aircraft evacuation doors. The rapid and automatic deployment of slides is a crucial factor in passenger evacuation, and whilst the regulations require a 90 second evacuation to be possible with only half of the available slides, any cases of a slide failing to deploy in actual accidents must be thoroughly investigated and corrected.

6. SMOKE HOODS

Smoke hoods as a potential life support system in a cabin filled with gaseous products of combustion have been researched and debated for at least the past fifteen years - off and on. Whilst maintaining the view that the provision of such things for donning by passengers during emergency evacuations is not practical they are, nevertheless, continuing to be examined. It is understood that of three types currently under review the type most favoured works on a filtration principle. The filter does not cope with all the 'nasty' products but I understand it prevents suffocation.

Whilst it may not be difficult to determine the basic physiological performance requirements, there are major psychological problems, not least of which are the claustrophobic effect, the reduced visibility, and the interference upon communication which will prevent the wearer hearing instructions during evacuation.

7 SECURITY OF CABIN FURNISHINGS DURING A CRASH

Having noted from some crash reports that overhead stowage bins came adrift and swung down over the passengers the design and adequacy of the catches is being scrutinised with a view to correcting the fault. It seems that whilst the catches are demonstratably adequate when static loads are applied they may not remain secure in the dynamic environment of some types of crash. It is thought that flexing of the metal fuselage structure may be more significant than general vibration.

8 CRASHWORTHINESS REGULATIONS AND COMPLIANCE

Perhaps the most comprehensive set of regulations governing crashworthiness and occupant survival are those developed for the Supersonic Transport aircraft. These are known as TSS Standards, and Standard No. 5-5, in addition to defining the safety objectives, contains very stringent requirements for cabin design, fuel tanks, landing gear, nacelles and engine mountings, systems design, and vital actions in the case of a crash. It also defines the type of analysis that is required to be carried out by the Constructor. For example, these state:-

a) "The Constructor should demonstrate that the behaviour of the aeroplane in crash landing conditions is acceptable by studying the failure characteristics of the structural elements affected by a crash landing and their effects on safety, and by studying the behaviour of the aeroplane in typical crash cases on landing and take-off".

b) "The Constructor should study the failure characteristics of the structural parts directly affected by a crash landing, the purpose of this study being to determine the seriousness of the effects which failure of these parts will have on the safety of the occupants. The study will in particularly enable an estimate to be made of the risk of failure of the fuel tanks".

In showing conformance with these objectives it was first necessary to agree a set of crash situations of moderate severity in which the occupant could reasonably expect to survive and which could most benefit from existing technology. It was noted from the records of subsonic aircraft accidents that these situations were those which occurred on or near airports; also that the landing gear either failed or broke off on impact, or for some reason was not lowered. The analysis carried out by the Constructors was based upon the accident summaries contained in the Air Registration Board (ARB) "World Airline Accident Summary" covering a period of four years 1968 to 1971. The object of the analysis was to determine the most frequent undercarriage failures and their causes and, in addition, to establish the frequency of fires associated with or resulting from undercarriage failures. During the four year period considered, there were 135 accidents involving failure of undercarriages; 16 of these were at take-off weight. Only 11 of the accidents (8% of the total number) involved fire, 1 was at take-off weight and 10 at landing weight. Of the 42 large turbojet aircraft accidents 7 of these involved fire. Extracts of this analysis are presented graphically in figures (6) to (9).

For the purposes of certificating the SST the following typical crash cases were agreed for analysis:-

a) Simultaneous failure of both main landing gears on landing.

b) Landing with all three landing gears retracted.

c) Collapse or failure to extend one main landing gear.

d) Collapse of the three landing gears at take-off.

e) Premeditated landing with nose gear up using Crew Manual technique.

These abnormal attitudes of the aircraft are shown in figures 1 to 4. They also show the height of the various evacuation doors from the ground whilst figure 5 shows the escape routes relative to the fuel tanks and engines.

For each of these crash situations an extensive structural analysis was undertaken from which predictions were made of anticipated structural damage or deformation. This was followed by a detailed study of possible consequential effects on all the various systems to ensure that;

a) flammable fluid spillage was unlikely to occur or that the quantity would be minimised.

b) electrical circuits would not be damaged such that essential crash-drill functions could not be accomplished.

c) the ability to evacuate the occupants was maximised taking into account possible areas of fire risk.

These studies proved to be both necessary and rewarding since various modifications were shown to be possible, and as a result, the risk of fire was further minimised and occupant survival prospects enhanced.

For example, the mounting structure for the rear part of the engine nacelles was redesigned to achieve a more predicable progression of rearward and upward crushing. The risk of tank rupture was thereby further minimised. However, it must be said that modifications can be very expensive and can have a serious impact on programmes. It was also interesting to note from the study that design features which had been provided for other airworthiness considerations also had a benefit in the crash situation. For example, the provision of two separate circuits of electrical wiring to the L.P. fuel shut-off valve ensured the survival of at least one of these in the event of an uncontained mechanical failure of an engine. It was also possible to refine the crew drills, such as instructing an action that would consume residual hydraulic pressure to cause the elevons to be in the correct state for rear escape slide deployment and use.

Although the prime objective was to prevent the release of fuel the Constructors recognised that accidents might occur in which tanks could also be ruptured by striking large obstacles and that fire might result. Having regard to the fact that during take-off and landing the four collector tanks on the Concorde contain warm fuel as a result of kinetic heating, the question arose as to whether this factor presented any particular hazard compared with subsonic operations. In other words, would a tank containing fuel at elevated temperature be more likely to explode within a period of five minutes if subjected to an external ground fire than one one containing cold fuel?

One of the difficulties in dealing with such a question was the definition of a "ground fire". Who was to decide the area and quantity of fuel involved, the intensity of the fire in terms of temperature and heat flux, the dynamics of the fire in varying wind conditions, and many other factors? Of course there is not such a thing as a "Standard Ground Fire".

At the time this was under consideration the FAA were instituting a series of crash fire studies and tests at NAFEC in Atlantic City (reported in Ref.5) and they agreed at the Concorde Constructors' request to include some testing at elevated fuel temperatures.

The conclusion we drew from these tests was that there is little difference in the time to explosion (if one occurs at all) whether the fuel is initially warm or cold. This is because the prime factor is the time taken for the tank skin to reach hot surface ignition temperature and not the initial state of the fuel and ullage in the tank.

The NAFEC tests also revealed an interesting phenomenon of self-inerting within the tank for some external fire conditions. It seems that at slow rates of tank heating the hydrocarbons combine with oxygen thus preventing an explosion.

9. CABIN INTERIOR MATERIALS FIRE SAFETY

A considerable amount of research and development continues to be carried out into the role of cabin interior materials in post-crash fire situations. Of course, the results of this work will also pay dividends in the in-flight cabin fire situation. The results obtained from this kind of research will be of direct concern to aircraft manufacturers inasmuch as they influence the possible promulgation of new airworthiness regulations. Over the past decade of aircraft designing activity the Constructors responded to three main Notices of Proposed Rule Making (NPRM) issued by the FAA. These were specifically addressed to "Fuel System Explosion Prevention" e.g. nitrogen inerting, "Compartment Interior Materials Toxic Gas Emissions", and "Smoke Emission from Compartment Interior Materials". In August 1978, after two Public Hearings, one on fuel system fire safety and one on interior materials, all three notices of proposed rule making were simultaneously withdrawn as being inappropriate at that time and state of knowledge. This withdrawal action was taken in conjunction with the establishment of the SAFER Committee.

In spite of the withdrawal of these notices the aircraft manufacturers continued with their research in the hope that, by extending their knowledge of material combustion, passenger survivability might be enhanced. It is now widely acknowledged that material combustion and the effect of the resultant gaseous products on passenger survivability is extremely complex. Indeed, it defies comprehension by many.

Meaningful test methods having the necessary simplicity for manufacturers to evaluate the overall combustion hazard of materials either do not exist or are not sufficiently developed. Furthermore, manufacturers are not authorised to experiment with animals, but even if they were, this would be impracticable for routine screening of materials.

Faced with these constraints, British Aerospace decided to conduct some full-scale tests to provide correlation between smoke density and loss of visibility. In addition, a theoretical evaluation of the hazard from toxic gas effects related to the hazard due to loss of visibility was made. The exercise was considered worthwhile at the time since the smoke and toxicity data available related to what we might now term "older materials". It was hoped that the results would point a new course of direction in the selection and development of materials whilst more specialised research was conducted elsewhere.

10. DETAILS OF CABIN SMOKE TESTING

Pyrolysis of cabin furnishings will in general produce smoke and a mixture of toxic gases. These products may have any or all of the following effects deleterious to a subject's ability to escape from a burning cabin:-

a) Deterioration of visibility due to light attenuation by smoke.

b) Deterioration of visibility due to lacrymatic effects of smoke.

c) Deterioration of visibility due to lacrymatic effects of noxious gases.

d) Physiological effects of breathing hot and/or irritant and/or toxic gases, other than lacrymatic effects.

e) Psychological effects of (a), (b), (c) and (d).

The smoke test conducted was concerned solely with the effect of light attenuation on visibility (i.e. (a)), and experimental investigation of any of the other listed effects was precluded by practical considerations. For example lacrymatic and irritant effects of smoke or gases, and psychological effects would be very difficult to define and measure.

10.1. TEST FACILITY

It was suspected that ambient lighting level could have a significant effect on visibility through smoke. For this reason it was considered that, in order for test results to be applicable to aircraft cabin situations, it was necessary to use a test chamber that was reasonably representative of a typical aircraft cabin, particularly with regard to windows and artificial lighting arrangements. A VC10 forward fuselage shell was in fact utilised. It was completely unfurnished, but any effect on ambient light levels due to different internal surface absorption and reflection characteristics of a bare and a furnished cabin were not considered likely to be significant.

The fuselage section (see Fig. 10) was divided by a bulkhead containing an observation window into a test section approximately 30 ft. long and a small observation and control area. Removable blackout covers were provided for cabin windows, and a blackout curtain was fitted over the observation window.

Simple overhead lighting units intended to be representative of typical aircraft units were installed. Illuminated distance markers were hung from the cabin roof at 5 ft. intervals along the centre line to provide a visibility datum. A typical internally illuminated aisle exit sign with red letters on a white background was mounted at a representative height on a carriage which could be moved along the cabin and positioned at known distances from the observation window. The letters were 1.6 in. high with 0.3 in. stroke width.

A smoke generator, controllable from the observation area, was positioned in the test area adjacent to a large electric fan provided to ensure even smoke distribution.

A smoke meter situated near the centre of the cabin consisted of a constant voltage collimated light source directed at a photo conductive cell 3 ft. away, both components being mounted on a common beam. Smoke meter output, which was roughly proportional to transmittance of the light path, was measured on a milliameter and continuously monitored on a paper trace recorder. The smoke meter was provided with a remotely operated shutter for zero calibration.

10.2 TESTING CONDUCTED

10.2.1. Preliminary:

Preliminary runs were conducted to checkout the facility and in particular:-

a) Ascertain that smoke distribution was even, both vertically and horizontally along the cabin.

b) Ensure that the smoke meter output was independent of ambient temperature, ambient lighting level, and fan induced vibration.

10.2.2. Calibration:

a) The smoke meter was calibrated using filters of measured optical density. This was repeated five times during the course of subsequent testing and provided calibration curves (one for the galvanometer, one for the paper trace recorder) of actual density/ft. against indicated transmission.

b) The cabin lighting system was calibrated using a Magnetron D 15 light meter (reading to 0.1 lux at $\pm$ 5%). With a given exit sign voltage this allowed marker light and interior light voltages to be set such that the illumination level with blackouts approximated to FAR minimum emergency requirements (i.e. at 24 inch height along cabin centre line vertical flux read at 40 inch intervals should give a lowest reading of 0.025 lumen/ft^2 minimum and an average of 0.06 lumen/ft^2 minimum).

c) An exposure photometer (measuring surface brightness) was used to set the exit sign voltage to a value giving a background brightness equal to FAR requirements (25 ft - lambert minimum).

10.2.3. Observer Vision Standard Effects:

Limited testing was conducted to attempt to establish if there were any major differences in observations between different observers. Eight observers were used and the following factors considered:-

a) Vision standard.

b) Adaptation rate (to change in light level).

c) Use of vision correction.

d) Age.

10.2.4. Visibility Testing:

Testing was initially conducted to establish the maximum smoke density at which the exit sign and distance markers could be seen for a given distance from the observation window. Subsequently a high intensity bulb positioned near the floor was substituted for the exit sign. When operated at their design voltage, visibility of these bulbs was not good. They were therefore used at a gross overload voltage (2-3 times design voltage).

The testing was conducted for four cabin illumination levels:-

a) Total Blackout (within capability of window screens, and with very dim illumination being given by exit sign and marker lights).

b) Emergency Lighting Level - blackouts on, and exit sign, cabin lights and marker lights on at voltages established in paragraph 10.2.2. (b) and (c).

c) Dull Daylight - blackouts off and heavy cloud outside, exit sign and marker lights on.

d) Bright Daylight - blackouts off and little or no cloud, exit sign and marker lights on.

Experimentation with different observation methods was carried out and a standard observation method for each lighting configuration envolved. Each method was basically intended to provide a constant level of observer vision adaptation for each type of test prior to and during each observation.

For the Total Blackout and Emergency Lighting tests ((a) and (b)) the lighting level in the control and observation area was maintained at a level approximating to that produced by normal aircraft lighting. The observer was adapted to this lighting for a minimum of 5 minutes prior to each observation, which was made from between the observation window and the blackout curtain.

For the Dull Daylight and Bright Daylight tests ((c) and (d)) the exterior door of the control and observation area was opened and the observer exposed to daylight between observations.

Each of these adaptation techniques was designed to approximate to the situation that an aircraft occupant might be expected to experience prior to an emergency evacuation in night and daytime situations repectively.

The actual observation was of 5 sec. duration, at the end of which time the observer decided whether or not:-

a) The exit sign was readable.

b) The exit sign illumination or high intensity bulb illumination (as applicable) was visible.

c) Each distance marker was readable.

d) Each distance marker illumination was visible.

For each run a series of observations was made with smoke density increased by a small increment between each observation. At the point where any of the events listed above occured (e.g. exit sign unreadable at one observation, having been readable for the previous observation) the smoke meter reading was recorded and the paper trace marked. By decreasing the sign or bulb distance from the observer and continuing to increase density, characteristics of indicated transmission vs observation distance for threshold readability and visibility of exit sign or high intensity bulb, and markers, were obtained. Using the smoke meter calibration curve (see paragraph 10.2.2. (a)) the characteristics were converted into actual density/ft vs observation distance.

A number of runs were conducted with the exit sign for each of the four lighting configurations. There were fewer repeats with the H.I. bulb but all four configurations were again covered.

10.3. RESULTS OF SMOKE TESTS

10.3.1. Preliminary Testing:

The results of this testing (see paragraph 10.2.1) showed that an even smoke distribution throughout the cabin was obtained within a few seconds of switching off the smoke generator, and that the natural smoke decay rate was low.

The smoke meter was found to be quite insensitive to ambient lighting level, temperature variation, and vibration; and smoke condensation on the lenses was not found to be a problem. Some wandering of the 0 and 100% meter data was experienced, believed due to photo cell drift, but it was found possible to allow for this adequately.

10.3.2. Observer Vision Standard Effects:

An observer with poor vision (e.g. myopia) could, of course, be unable to read the exit sign even in the absence of smoke. With the particular observers employed however, this did not occur, although there was a sufficient range of vision standard to show up any major effects in smoke.

The testing conducted was not exhaustive but was adequate to show up any significant trends. There was some scatter in results between observers and between runs but this was of a fairly small order. No consistent differences that could be correlated to the factors listed in paragraph 10.2.3. were found.

10.3.3. Visibility Testing:

No significant variation in results was found with varying adaptation times and light levels prior to and during each observation. However, the standard observation methods evolved (para 10.2.4.) were employed to ensure consistency.

In most cases repeatability was very good. The difference in observation distance between two similar tests for the same event to occur at the same density/ft. was in general less than 1.5 ft.

Figures 11 and 12 show plots of density/ft. vs distance for exit sign readability and visibility limits respectively. Each curve represents mean results of two or three test runs.

It can be seen that there is negligible difference between results for total blackout and emergency lighting conditions. However, for daylight conditions there is a marked adverse effect on both readability and visibility compared to blackout conditions, giving a difference in terms of distance (at a particular density) in the order of 3ft. at near distances and 10 ft. at far distances. This is an expected effect in this situation as an observer sees by means of the contrast between the object (e.g. exit sign) and the background, i.e. the smoke. At higher ambient lighting levels the particles of smoke are more highly illuminated and contrast is low.

The difference between readability and visibility is seen by comparison of Figs. 11 and 12 to be very small for near distances and in the order of 1 to 5 ft for far distances.

High intensity bulb visibility when operated at gross overload voltage is shown in Fig. 13. By comparison with Fig. 12 it is seen that the bulb is visible at a significantly greater distance than the exit sign illumination. Even though the H.I. bulbs were overloaded their life was found to be several times as long as that guaranteed by the manufacturers.

However, it was difficult to assess what potential value a high intensity light source may have. It cannot be assumed that either calm or panic stricken escapees would necessarily be attracted towards it; the reverse could be the case.

10.4. THEORY

Relevant theory is considered below in some detail to emphasise the difference between optical density (D) and specific optical density (Ds).

10.4.1. Definitions:

a) Light transmission through a medium with photometric attenuation coefficient σ is defined by Bouguer's Law (also called Lambert's or Beer's Law):-

$$F = F_o e^{-\sigma L} \qquad (1)$$

b) Transmission T (%) is defined by:-

$$T = 100 \frac{F}{F_o} \qquad (2)$$

c) Optical density D is defined by:-

$$D = \log_{10} \left(\frac{F_o}{F}\right) \qquad (3)$$

from Eq. (2) $\quad \frac{Fo}{F} = \frac{100}{T} \qquad (4)$

from Eq. (3) and (4) $\quad D = \log_{10} \left(\frac{100}{T}\right) \qquad (5)$

This is a useful relationship as smoke meters read transmission, and optical density is usually required.

10.4.2. Specific Optical Density:

Specific optical density of a material is defined by:-

$$Ds = D \frac{V}{AL} \qquad (6)$$

Where D is the density measured at a given time from start of combustion, and V and L are as defined under Nomenclature.

Photometric transmission and optical density as defined in paragraph 10.4.1. are by their definitions related only to light attenuation in a medium (e.g. water, glass, smoke) and have no specific relationship to the production of smoke from a burning material specimen.

Specific optical density on the other hand is related only to smoke produced from a burning material. Its purpose is to provide a measure of the smoke producing properties of materials. Implicit in the definition of Ds are the assumptions that when a material is burnt in a chamber the optical density of the smoke produced is:-

a) Directly proportional to the specimen surface area.

b) Inversely proportional to the chamber volume.

It is known that these assumptions are not strictly correct and that there are other factors affecting smoke density produced from burning (e.g. temperature, material thickness, etc.).

Smoke density, and hence Ds value also, obviously depends on the time from start of burning. The practice with the N.B.S. chamber (see below) was to quote the Ds values at 1 1/2 min. and 5 min. from start of combustion, although for a complete definition, a time based plot is required.

It is stressed that on its own the Ds value of a material does not give any indication of what smoke density may be produced by burning a piece of the material. Optical density/ft. depends on Ds, A, and V. Thus in a given cabin volume 1 ft^2 of material used in, say, a light fixture and having a Ds value of 600 will produce almost twice the smoke density of for example 20 ft^2 of carpet having a Ds of 16.

The N.B.S. smoke chamber is commonly used to measure Ds values. For this chamber:-

$$V = 18 \text{ ft}^3$$

$$A = 4.56 \times 10^{-2} \text{ ft}^2 \quad (2.96 \text{ in}^2)$$

$$L = 3 \text{ ft.}$$

i.e. $$\frac{V}{AL} = \frac{18}{4.56 \times 10^{-2} \times 3} = 132$$

from Eq. (5) and (6) $$Ds = \frac{V}{AL} \log_{10} \left(\frac{100}{T}\right)$$

i.e. $$Ds = 132 \log_{10} \left(\frac{100}{Tt}\right)$$

where Tt is the transmission measured by the N.B.S. chamber smoke meter.

10.5. EFFECT OF VISIBILITY LOSS

The hindrance to evacuation of a cabin due to combustion products is obviously related, among other things, to the degree of visibility loss in the cabin due to smoke, i.e. related to smoke density. This testing was not aimed at investigating this hindrance/visibility relationship and it would be difficult to devise means of doing so. To assess the meaning of the testing that was done on the density/visibility relationship the rather arbitrary concept of a limiting visibility loss has been used. It is assumed that there is a certain minimum distance Lc' over which an average subject must be able to see a given object in order to be able to escape in an acceptable time.

Airworthiness regulations require that an exit sign be visible from every seat position which, for a typical modern transport, may constitute a distance of 30 ft. or more. However, a subject's ability to escape would not necessarily be compromised just because an aisle exit sign were not visible. The natural reaction could be to pass along the aisle using seat backs as a guide until close enough to an aisle and/or over-door exit sign to see it. This represents for the over-door sign a distance equivalent to 2-3 seat widths plus half the aisle width. Based on this criterion, visualisation of likely conditions in a furnished cabin interior, and general experience in the smoke filled test chamber, a limiting visibility distance (Lc') of 6 ft. is selected. If it is assumed that an exit sign must be readable at this distance the corresponding limiting density/ft. (Dc'/Lc') can be found from Fig. 11. Taking the bright daylight situation as the most adverse case a limiting density of 0.50/ft. is obtained. Note that at this density/ft. the exit sign can be read at 9 ft. under blackout conditions.

10.6. LIMITING Ds AND MATERIAL AREA VALUES

From paragraph 10.4.2. and in particular Eq. (6) it is seen that the density/ft. produced by combustion in a closed volume is given by:-

$$\frac{D}{L} = Ds \frac{A}{V} \qquad (7)$$

The limiting visibility distance Lc' (see paragraph 10.5) corresponds to a limiting density Dc' which will be produced by burning in a given volume a piece of material of surface area Ac'.

from Eq. (7) $$\frac{Dc'}{Lc'} = Ds\,\frac{Ac'}{Vc} \qquad (8)$$

i.e. $$Ac' = \frac{Dc'}{Lc'}\,\frac{Vc}{Ds} \qquad (9)$$

From this relationship the maximum area of material of a given Ds value that can be burnt without exceeding given density limits can be found. Results are plotted in Figs. 14 and 15 for the bright day-light and emergency lighting level cases respectively, for a cabin volume of 6000 ft^3 (typical of a small/medium sized passenger transport aircraft).

11. TOXIC GAS EVALUATION

11.1 General

The F.A.A. report used (ref. 6) presents the results of flaming and non-flaming pyrolysis in an N.B.S. smoke chamber of 143 typical cabin furnishing specimens which are classified as fabrics; rugs; and flexible, semi-rigid sheets and laminates. Maximum concentrations of toxic gases are presented for both test conditions for each specimen. Concentrations of the following gases are reported:-

Carbon Monoxide	CO
Hydrogen Cyanide	HCN
Hydrogen Chloride	HCl
Hydrogen Fluoride	HF
Sulphur Dioxide	SO_2
Oxides of Nitrogen	$NO + NO_2$
Ammonia	NH_3
Chlorine	Cl_2
Phosgene	$COCl_2$

When a specimen is burnt in a closed volume both smoke optical density per foot and toxic gas concentrations are assumed to be proportional to A/V (specimen area divided by chamber volume, see paragraph 10.4.2.). The test results were analysed in an attempt to estimate for each sample whether, as the factor A/V increases, maximum smoke density could become high enough to cause sufficient loss of visibility to hinder evacuation without maximum toxic gas concentrations becoming dangerous, or vice-versa. A similar study was also made of irritation produced by various gases.

11.2 METHOD

Of necessity the toxic effects of the different gases had to be treated individually, i.e. synergistic effects are neglected. The following concentrations of the relevant gases are assumed to:-

a) produce irritation on brief exposure.

b) constitute an immediate danger to life for a 2 to 5 minute exposure.

TABLE 1

Based on information given in the ref. 6 report

	Concentration ppm						
GAS	CO	HCl	HCN	HF	SO_2	NH_3	$NO + NO_2$
(a) Irritation	-	35	-	30	35	500	25
(b) Immediate danger	10000	1500	250	150	500	2000	450

As for smoke density/ft.', concentrations of gases were assumed to be proportional directly to material surface area and inversely to the volume of the chamber in which combustion occurs.

i.e. $C \propto \frac{A}{V}$

Thus relating concertrations in a cabin to those in a test cell (suffixes c and t):-

$$Cc = Ct \frac{Vt}{Vc} \frac{Ac}{At} \qquad (10)$$

If a piece of material having the surface area Ac' related to visibility limitations is burnt, then the concentration in the cabin of a particular gas is:-

$$Cc' = Ct \frac{Vt}{Vc} \frac{Ac'}{At} \qquad (11)$$

from paragraph 10.6', Eq.(9)

$$Ac' = \frac{Dc'}{Lc'} \frac{Vc}{Ds}$$

$$\text{i.e.} \quad Cc' = Ct \frac{Vt}{At} \frac{Dc'}{Lc'} \frac{1}{Ds} \qquad (12)$$

for the N.B.S. chamber

$$Vt = 18 \text{ ft}^3$$

$$At = 0.0456 \text{ ft}^2$$

$$\text{i.e. from Eq. (12)} \quad Cc' = 395 \frac{Dc'}{Lc'} \frac{Ct}{Ds} \qquad (13)$$

The F.A.A. report gives both maximum Ct (for each gas given off) and maximum Ds for each specimen under flaming and non-flaming conditions.

By assuming a number of limiting optical density values Dc'/Lc' the corresponding concentrations in the cabin (Cc') of each gas given off by each specimen under either test condition may be found from Eq. (13).

For a given value of Dc'/Lc', if the concentration Cc' of any gas given off by a particular specimen under flaming and/or non-flaming conditions is greater than the respective limiting value at (b) in Table 1, then the toxic effects were considered to be more important than obscuration effects for this specimen, and vice-versa. Similarly it can be seen whether irritation is a significant factor for a certain material. By taking a number of values of Dc'/Lc' plots can be made of the percentages of the 143 specimens that are toxicity limited, and for which irritation is significant.

It is recognised that these criteria were fairly arbitrary in that:-

a) maximum gas concentrations were compared with the limiting values in the Table, which are steady state.

b) the limiting values tabulated can, of necessity, be approximate only.

c) the time factors involved in smoke and gas build-up were not considered (due to lack of data).

d) of necessity no allowance was made for the contribution to the toxicity of a mixture by a particular gas at an individually non-lethal concentration.

11.3 RESULTS OF TOXIC GAS STUDY

Fig. 16 shows the percentage of specimens for which the maximum concentration of each gas yielded under either or both burning conditions exceeds the limiting toxicity value. For example, if there is burnt a sample of each specimen of sufficient surface area to produce a maximum optical density per foot of 0.5 in a given volume, then, from Fig. 16, 3% of the specimens produce a maximum concentration of carbon monoxide (CO) exceeding the limiting concentration of 10,000 ppm. Hydrogen chloride (HCl) was seen to be the gas most frequently present in dangerous doses.

The percentages of specimens for which any gas exceeds toxicity and irritation limits are presented in Fig. 17, along with the bright daylight exit sign readability curve reproduced from Fig. 11. Taking a 6 ft. readability limit (Paragraph 10.5), Fig. 17 show that 13% of the specimens yielded one or more gases in concentrations exceeding the dangerous values. Irritant concentrations of the noxious gases occurred with a high proportion of the specimens before optical density becomes limiting, the most prevalent gas being HCl. For 6 ft. readability, irritation due to any gas occurs with 74% of the specimens. In about 90% of these cases HCl exceeds irritation limits.

Attempts were made to devise the best possible method for this study, but with the limited information available the criteria used were fairly arbitrary. More recent designs of aircraft have benefitted from the knowledge gained from studies of this kind and more advanced materials are being used. In particular, the new generation of aircraft will have fewer P.V.C. type of materials and this will reduce the prevalence of HCl as a combustion product. This analysis predicted that HCl was the most abundant single gas and thus a reduction in the number of materials producing it is bound to affect the results.

Thus the results of this toxic gas study cannot be expected to represent in detail a realistic situation, and the method of analysis of necessity involved extensive simplifying assumptions. The results can therefore be expected to provide broad indications only. These are that it seems probable that for the majority of materials visibility loss is more likely than toxicity effects to hinder escape, but that irritant concentrations of gases are likely to be present in many cases without visibility being limited by smoke. The latter point may well be a significant factor as irritation is likely to have an adverse effect on vision.

12. CONCLUSIONS

1) The prevention of accidents continues to be a prime objective of Aircraft Constructors. However, faced with a multiplicity of airworthiness and crashworthiness aims the resultant product must inevitably be a careful optimisation of all the requirements, with an eye on "overall safety".

2) Crashworthiness studies of new aircraft designs, as currently defined in the Airworthiness Regulations, have been found to be essential and rewarding in reducing post-crash fires and enhancing survival.

3) The Constructors endorse the view that Anti-Misting Kerosene, if successful and practicable, could provide the greatest potential for saving lives in post-crash situations.

4) Research into cabin interior material combustion hazards continues to emphasise the extreme complexity of the problem, and it is not unique to the aircraft industry. In spite of the difficulties, research will continue since the results could have benefits for both in-flight and ground fire situations.

5) The aircraft industry will continue to effect evolutionary improvements but believes that perhaps we are struggling on the flat part of the law of diminishing returns. Application of technology that does not substantially increase safety may not be warranted. Whilst progressive improvements in post-crash fire reduction and occupant survivability might be realised by wider education, improved design disciplines and appropriate research programmes, it is difficult to envisage any major impact being effected in the short term; and the long term solutions will be very expensive.

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Abnormal attitudes

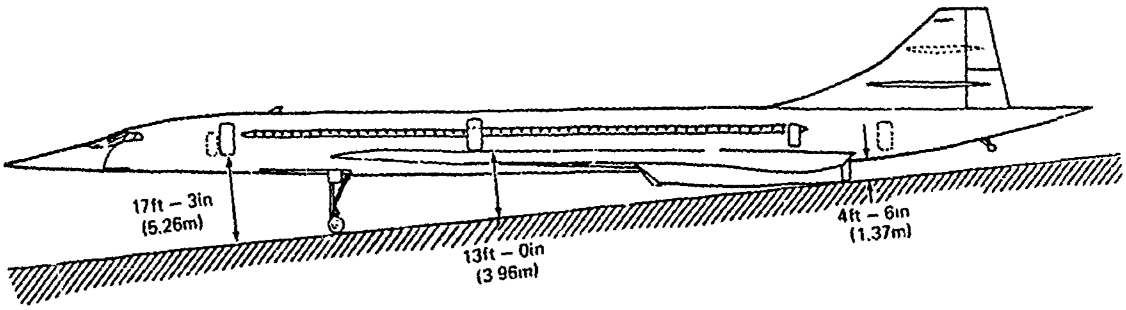


FIG. 1. Both main landing gears collapsed

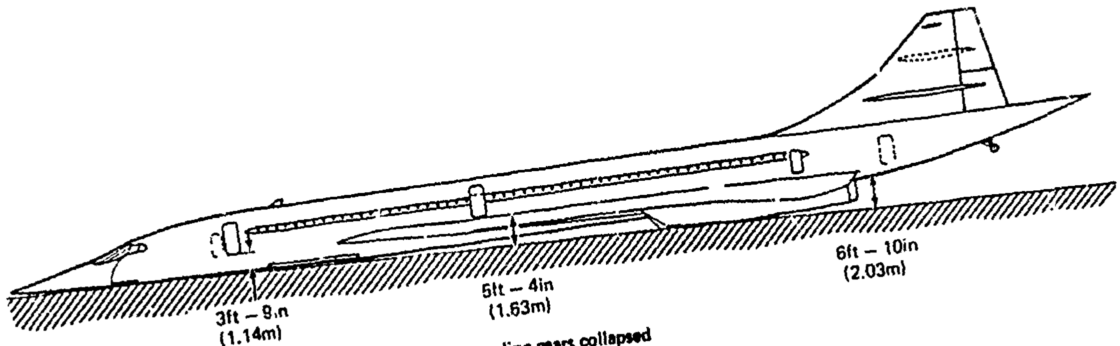


FIG. 2. All landing gears collapsed

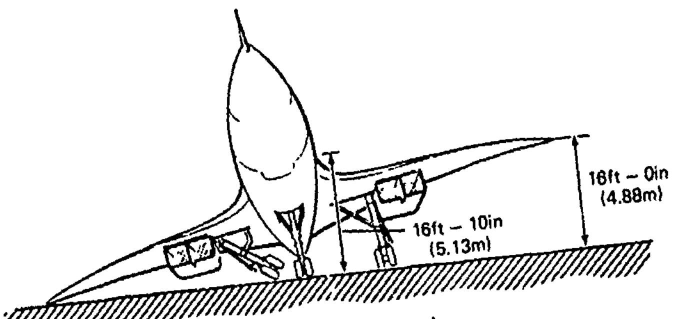


FIG. 3. One main landing gear collapsed

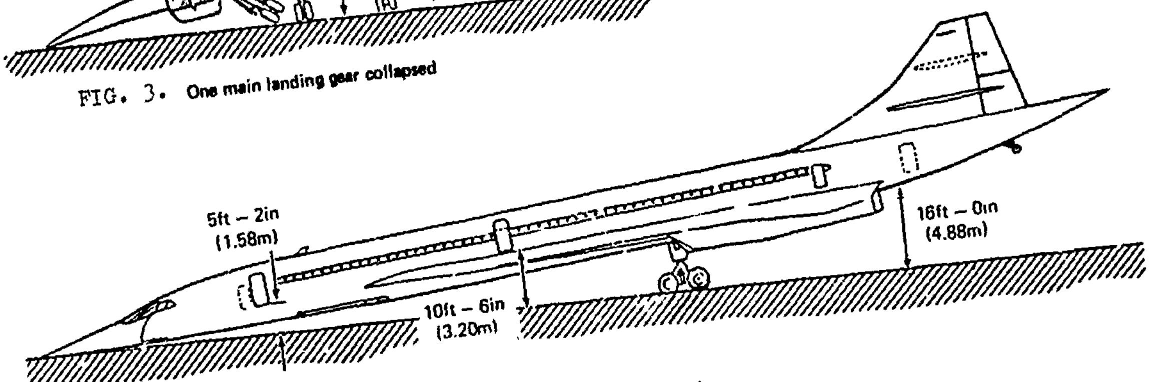
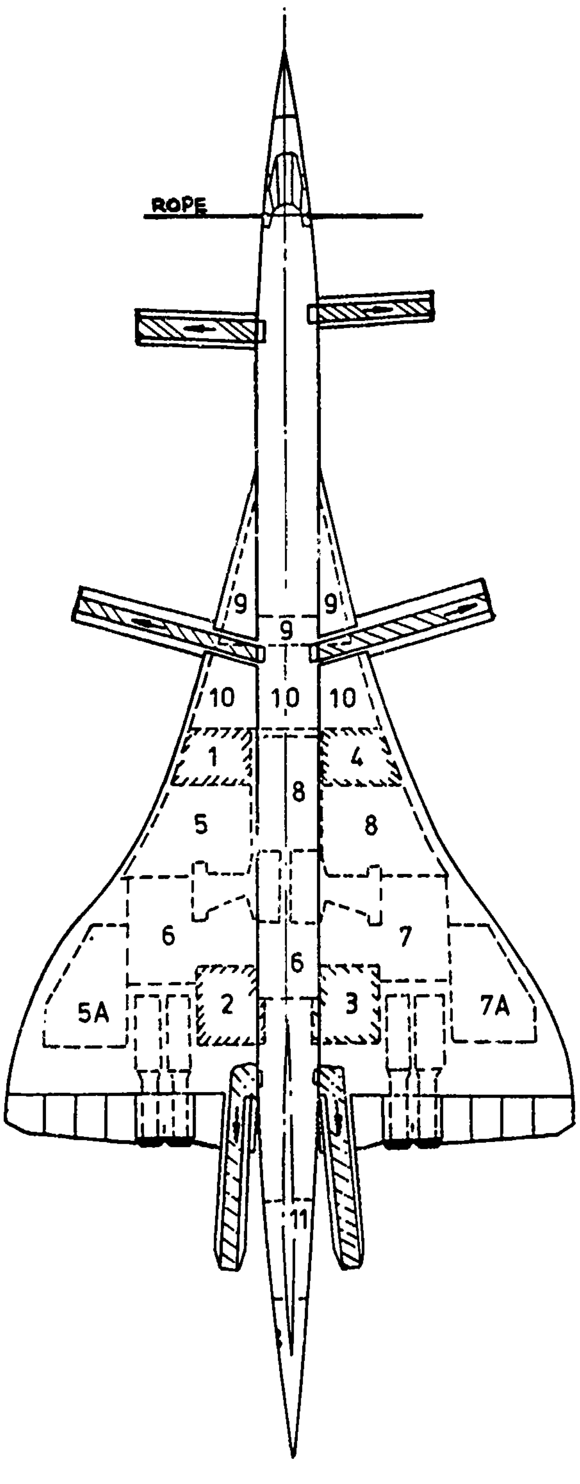


FIG. 4. Nose landing gear collapsed



THE PASSENGER CABIN HAS 3 OUTWARD-OPENING PLUG DOORS ON EACH SIDE OF THE FUSELAGE.
ALL THESE ARE CLASSED AS TYPE 1 EMERGENCY EXITS AND MAY BE OPENED FROM INSIDE OR OUTSIDE THE AIRCRAFT. EACH DOORWAY INCORPORATES A SELF-INFLATING AND AUTOMATICALLY DEPLOYED ESCAPE SLIDE OR SLIDE/RAFT.

SLIDING SIDE WINDOWS ARE PROVIDED AT EACH PILOT'S STATION AND ARE DESIGNED AS EMERGENCY EXITS FROM THE FLIGHT DECK. THESE WINDOWS CAN BE OPENED ONLY FROM THE INSIDE.

FIG. 5. EMERGENCY EVACUATION SLIDES

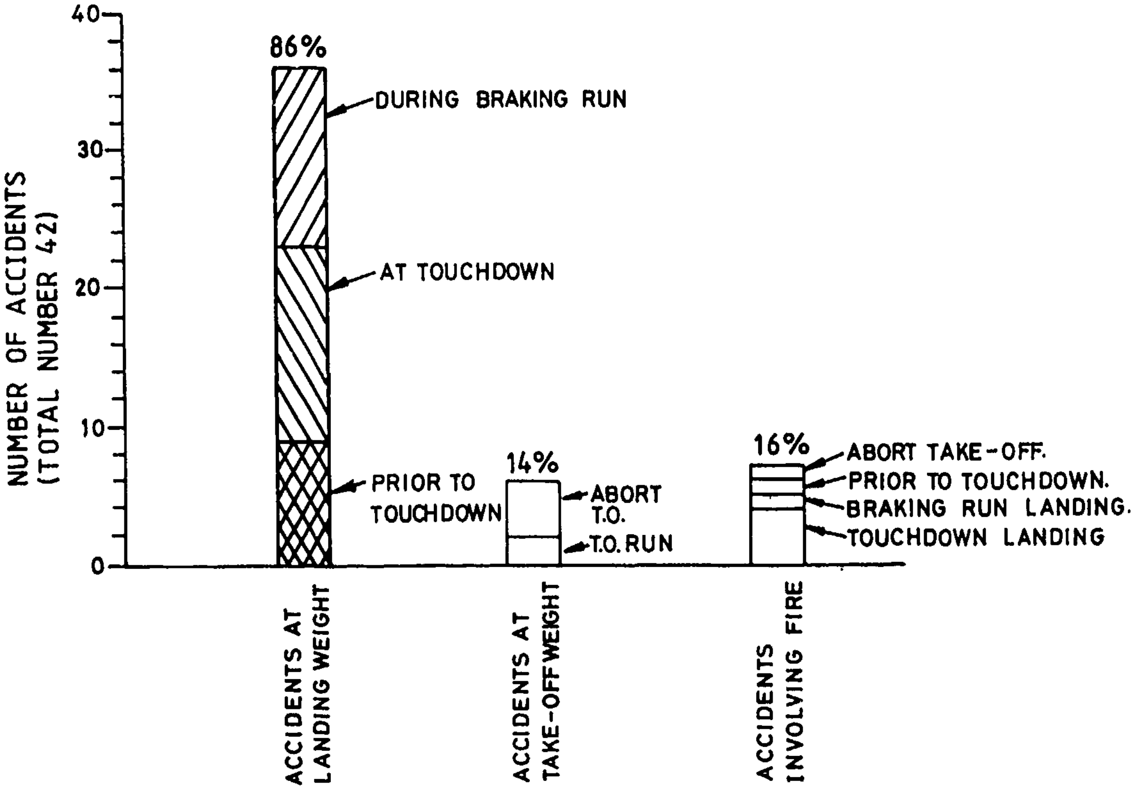


FIG.6. ACCIDENTS INVOLVING UNDERCARRIAGE FAILURE (1968-71). LARGE TURBO-JET AIRCRAFT ONLY.

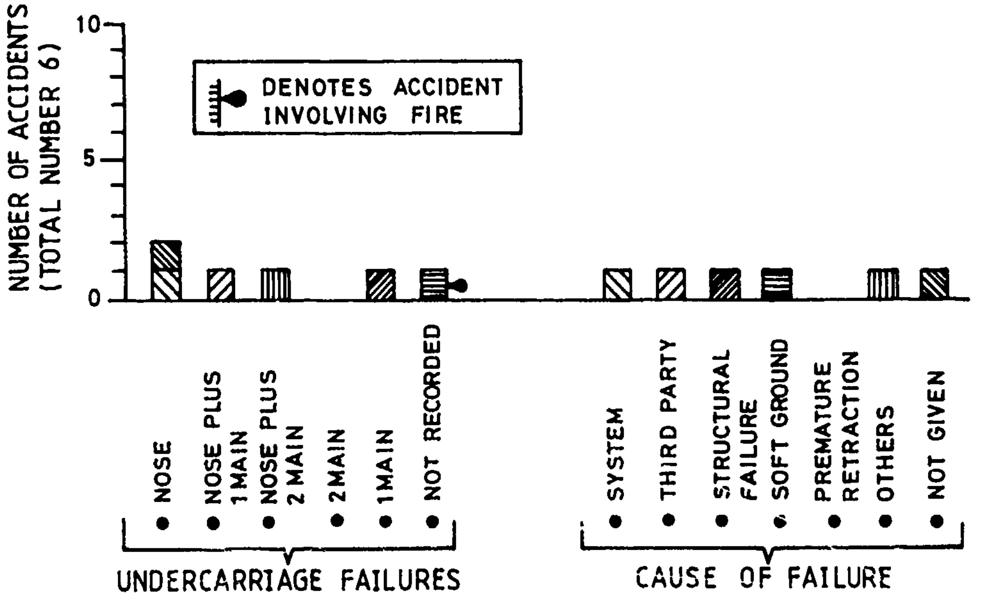
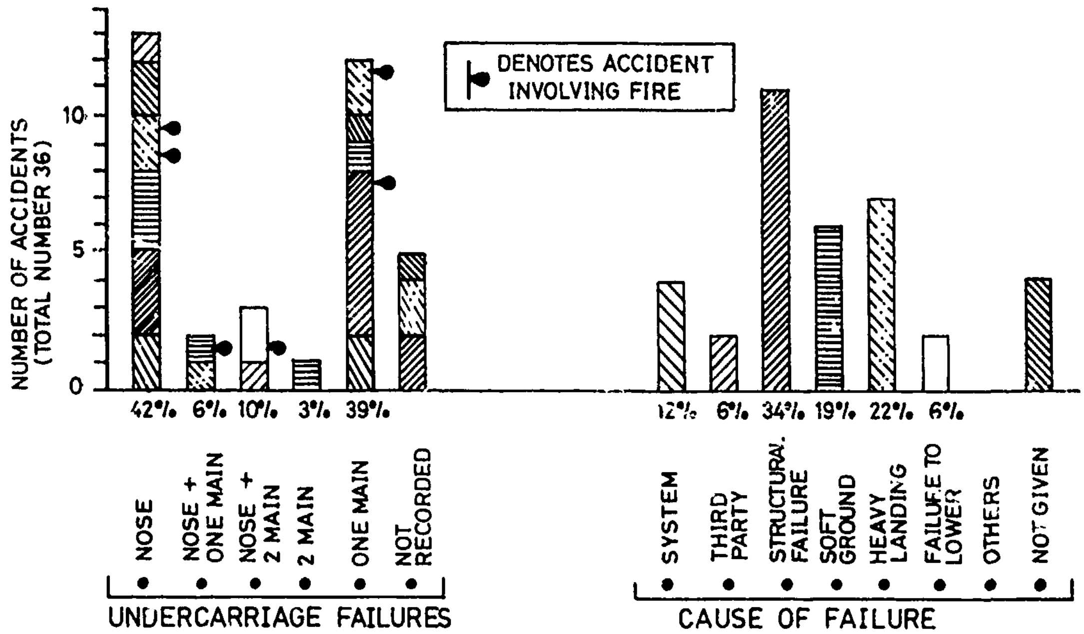


FIG.7. UNDERCARRIAGE FAILURE ACCIDENTS AT TAKE-OFF WEIGHT. LARGE TURBO-JET AIRCRAFT ONLY.



NOTE : THE PERCENTAGES REFER TO THE NUMBER OF ACCIDENTS TO TURBOJET AIRCRAFT AT LANDING WEIGHT. = 36 MINUS THE NUMBER OF CONFIGURATIONS OR CAUSES OF FAILURE NOT RECORDED IN THE A.R.B. ACCIDENT SUMMARIES.

FIG. 8. UNDERCARRIAGE FAILURE ACCIDENTS AT LANDING WEIGHT LARGE TURBOJET AIRCRAFT ONLY.

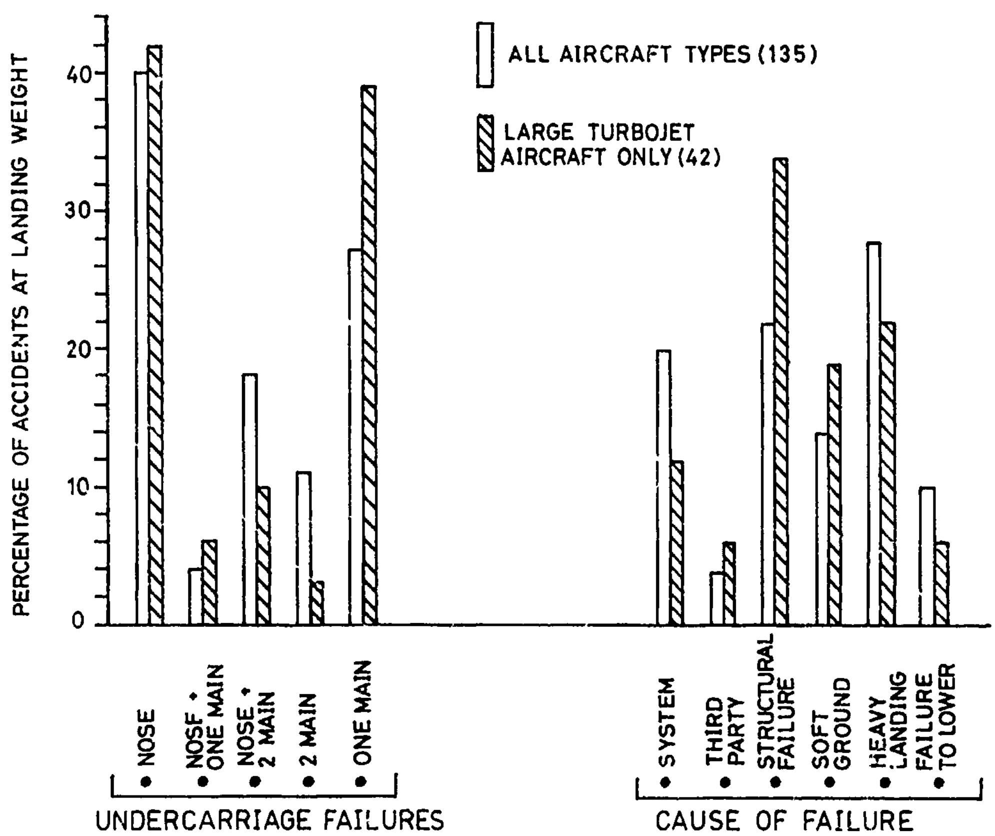


FIG. 9. COMPARISON OF RESULTS FOR ALL AIRCRAFT TYPES WITH THOSE FOR TURBOJET AIRCRAFT.

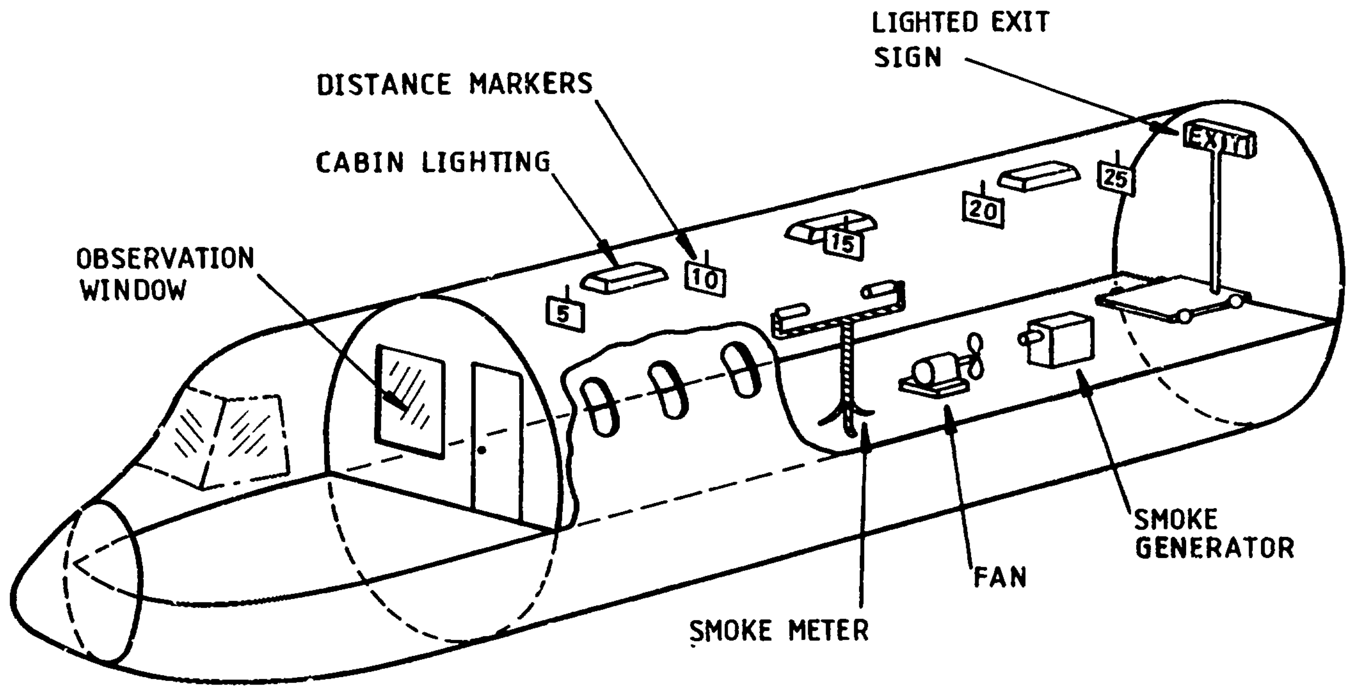


FIG.10. LAYOUT OF SMOKE TEST FUSELAGE

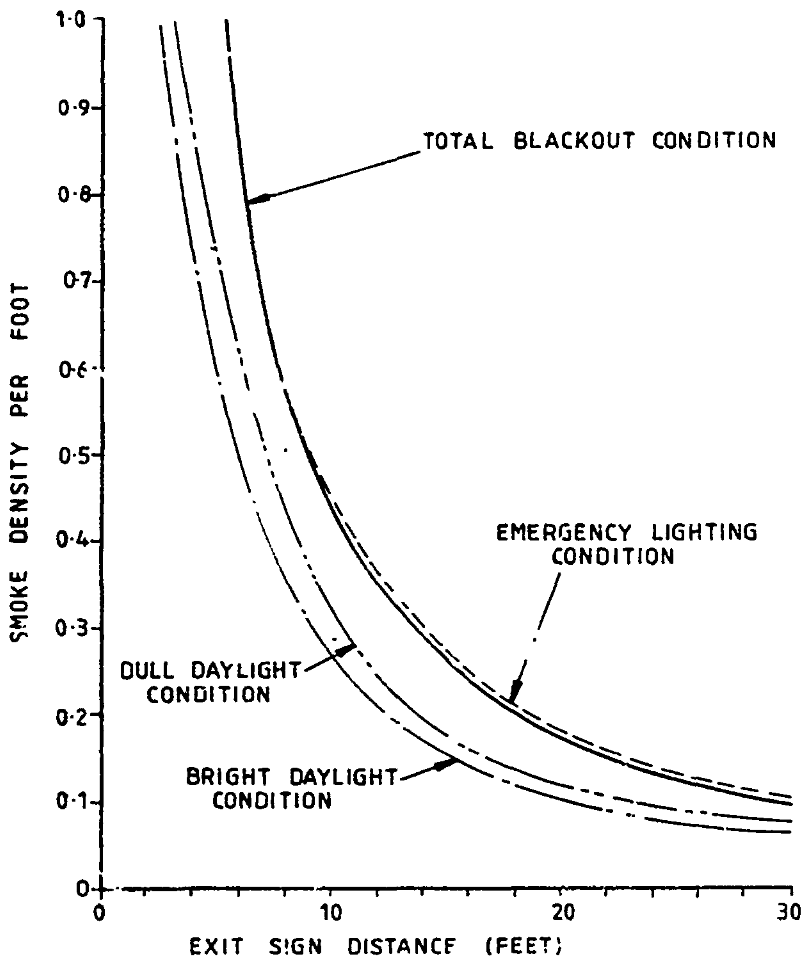


FIG. 11. LIMIT OF EXIT SIGN READABILITY

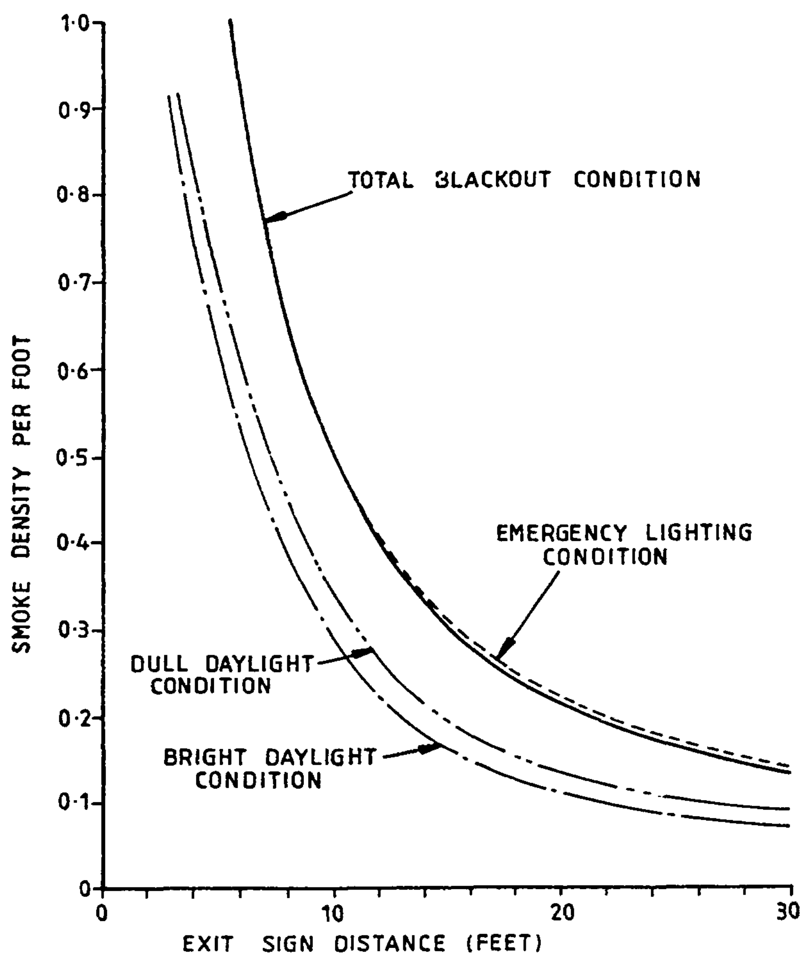


FIG. 12. LIMIT OF EXIT SIGN VISIBILITY

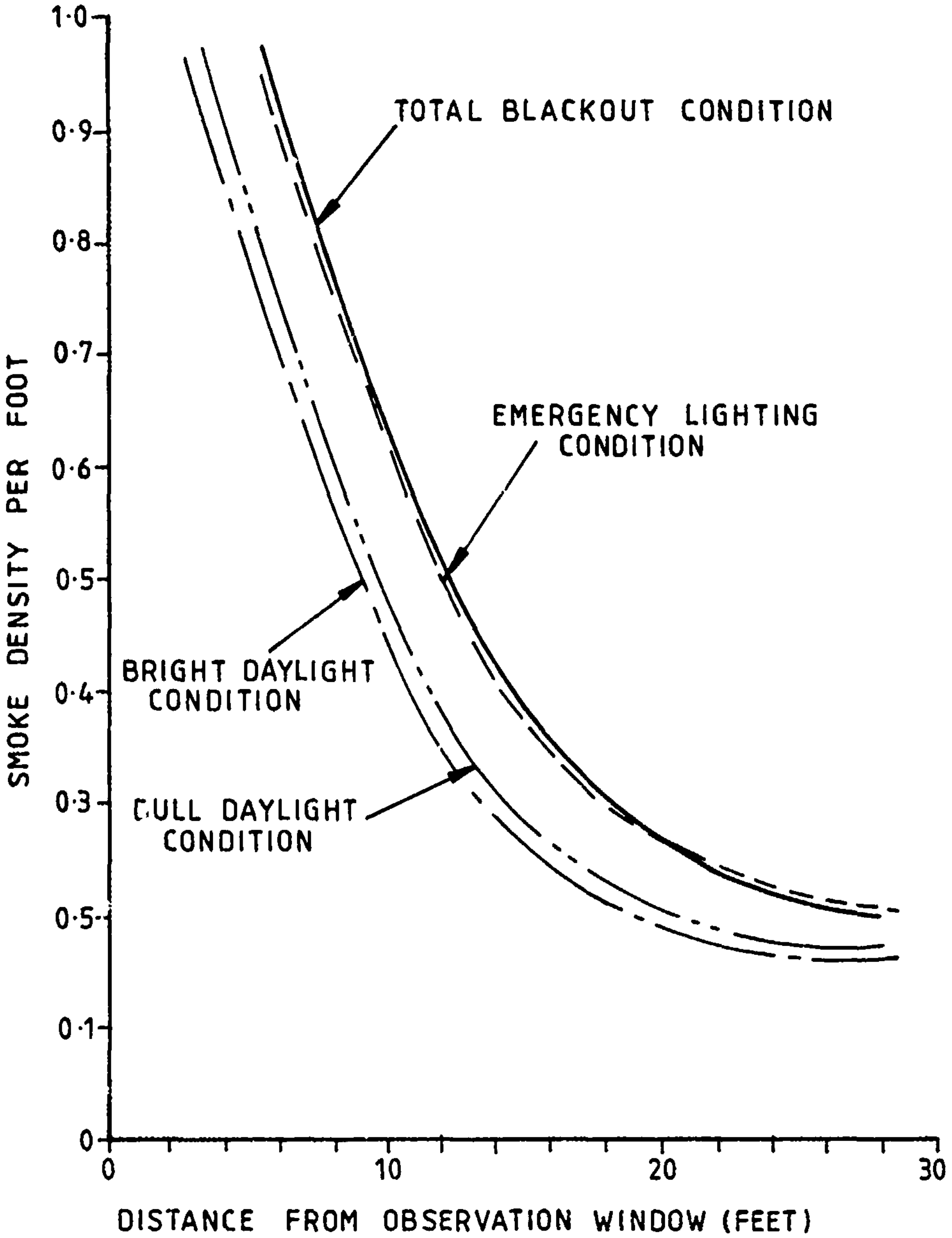


FIG.13. LIMIT OF HIGH INTENSITY BULB VISIBILITY

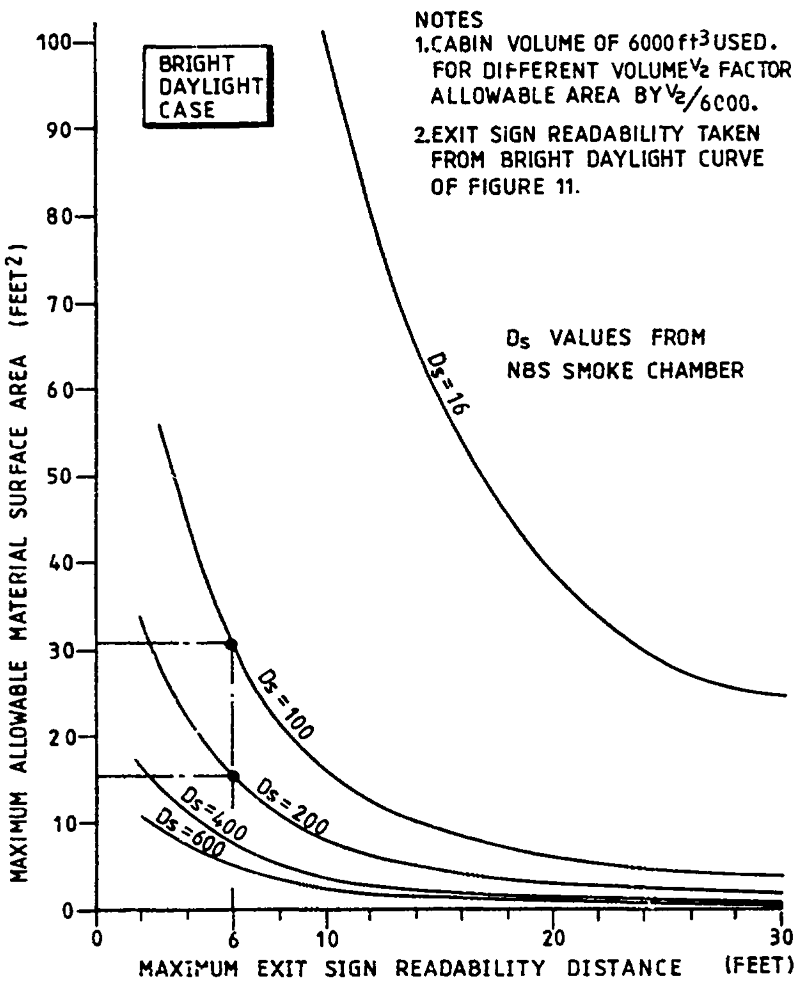


FIG.14. ALLOWABLE MATERIAL SURFACE AREA VS EXIT SIGN READABILITY DISTANCE

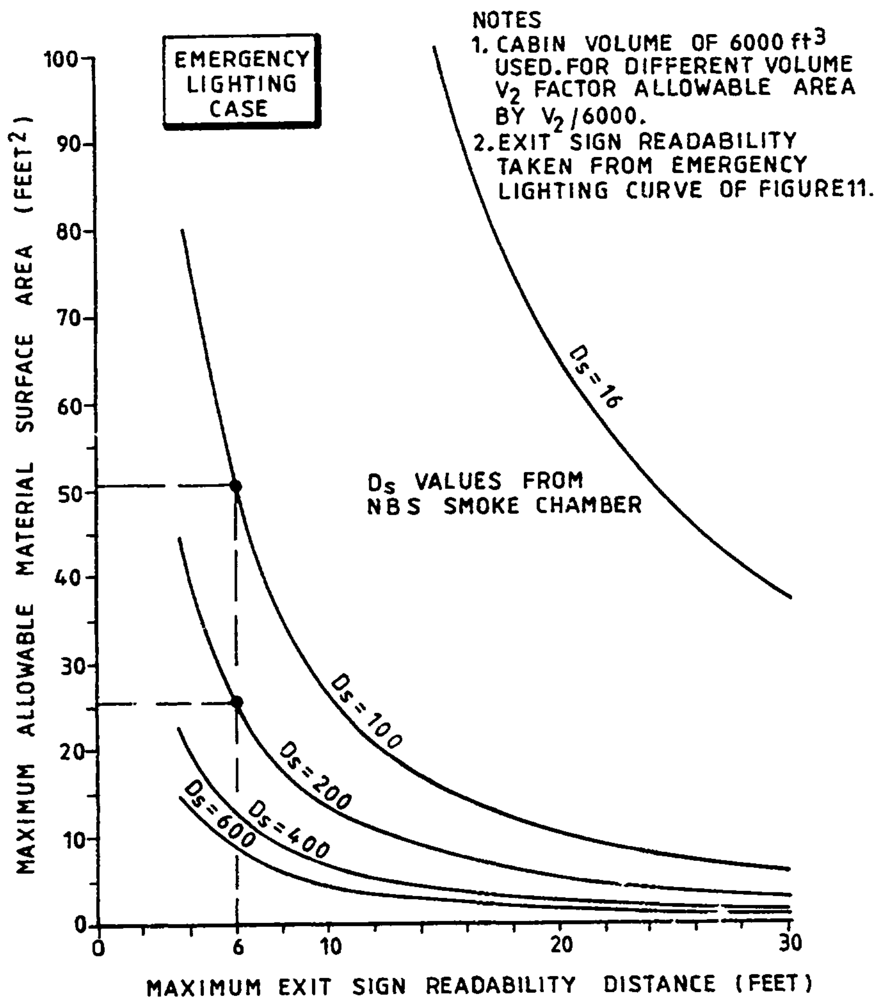


FIG.15. ALLOWABLE MATERIAL SURFACE AREA VS EXIT SIGN READABILITY DISTANCE.

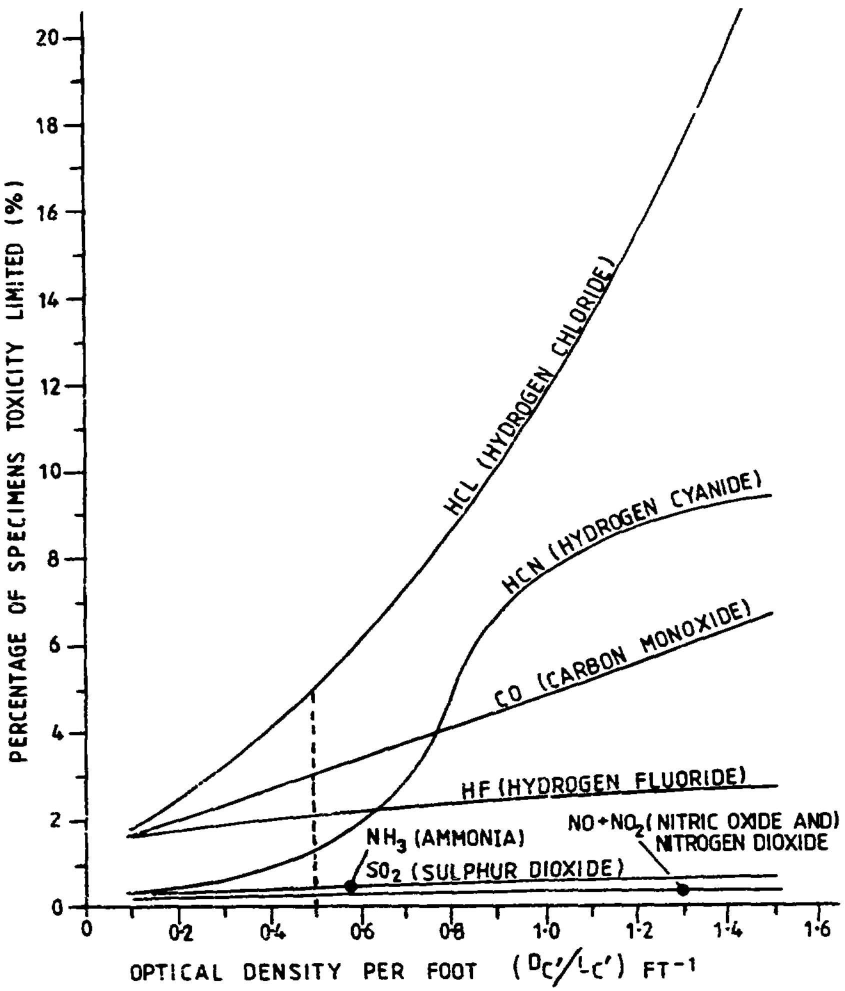


FIG. 16. PERCENTAGE OF SPECIMENS TOXICITY LIMITED FOR DIFFERENT GASES

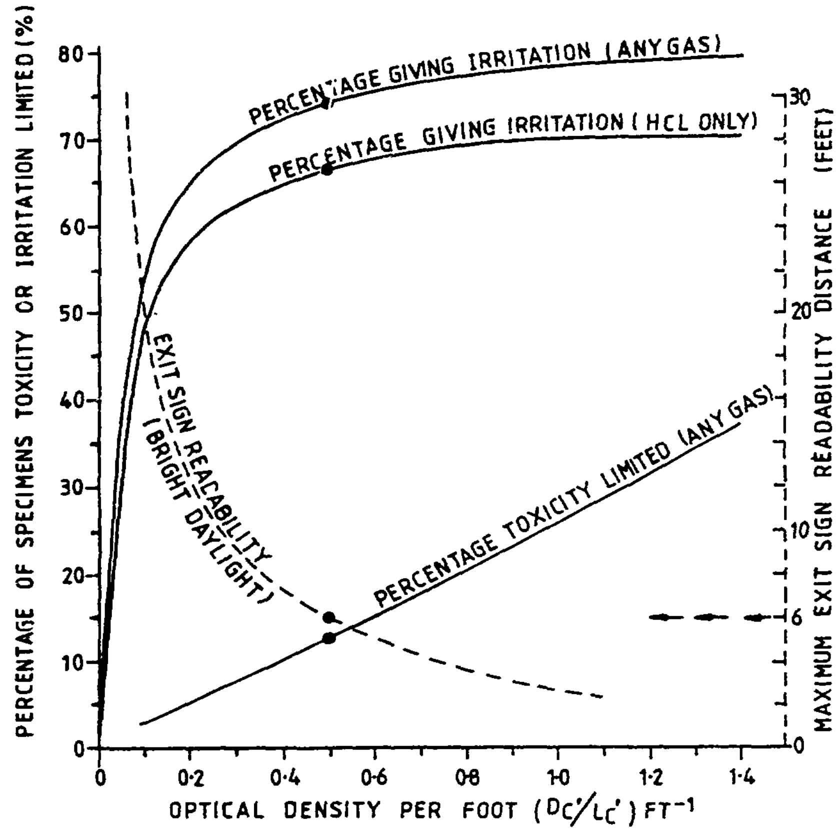


FIG. 17. COMPARISON OF IRRITATION, TOXICITY AND READABILITY

Aircraft Post-Crash Fire Fighting/Rescue

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SUMMARY

The fire fighting of post crash fires requires the use of quasi three dimensional acting agents and of quasi two dimensional actic agents at the same time.
Many substances inhibit the hydrocarbon-air/oxygen reaction and when adequately prepared, they can be used as a three dimensional acting agent, becuase they can be distributed in the volume. From these substances, which are listed, only the halon 1211 and the dry powders based on $KHCO_3$, K_2SO_4 and still $NaHCO_3$ are of importance for the mentioned purpose.
Mainly two dimensional acting agents are foams. Foams are needed for the extinguishment of the spill-or pool fires, which often follow a crash of an airplane.
The influence of the following properties of the foams on the extinguishing efficiency is discussed:

- surface tension of the water foaming agent solution
- concentration of foaming agent in the solution
- viscosity of the foam
- energy used to foam the water-foaming agent solution
- spreading velocity of the foam
- spreading distance of the foam
- expansion ratio of the foam

From the available test results on which could be made full use of a correlation between the specific extinguishing time and the size of the burning fuel area is deduced.
Also the influence of fuel properties, namely the boiling temperature and the viscosity, on the extinguishing efficiency of foams is described.
Furthermore an extinguishing technic, which takes in account the dependence of the extinguishing efficiency on the foam properties, is given.
The requirements for foam monitors, resulting from this technic, are shown.
In this connection the break-up of foam jets, produced by foam monitors is discussed.
On the basis of a limited number of test datas the extinguishing effieciency acchieved with the combined application of dry powder-halon and foam is outlined as well as the advantage of a combined use in the case that only a pool fire is existing.

Introduction

In a post-crash fire of an airplane all categories of fire may occur. The accident statistics show, that one has to deal with class A, B, under some circumstances class C and also class D and class E fires. [1, 2]
Class A fires mostly consist of fires of plastic materials a widely used material for the interior of an airplane and for cable insulation, but also parts of the wings and the fuselage are made from plastics. The fire of the cargo of an airplane is also often a class A fire. Fires of metals (Class D fires) have been observed too, as well as fires in the electrical installation. (Class E fires).
The most frequently and severest fires following a crash of an airplane are class B fires, the fuel fires.
This paper deals only with the fuel fires. After a crash one has to count with fires of a fuel mist, of running fires and fires of jets or sprays of fuel from damaged fuel lines and ruptured fuel tanks of engine fires and pool fires of different sizes.
These fuel fires can be divided roughly into two groups, the quasi two dimensional fires, namely the pool fires and the quasi three dimensional fires, the fires of jets or sprays of fuel, and so on.
In order to save lifes, these fires have to be extinguished in the shortest time as possible.
Today no extinguishing agent is existing which fulfills this demand alone. Dry powders and halons are the best extinguishing agents known for the extinguishment of quasi three dimensional fires because they can be distributed in the volume occupied by the flames. But these agents do not prevent reignition of the already extinguished fuel by hot parts or residual flames.
Extinguishing foams are suited best, for the extinguishment of pool fires in the presents of reignition sources.

Extinguishing agents for quasi three dimensional fires

Many substances in a gaseous or appropriate solid configuration have an inhibiting influence on the combustion reaction of hydrocarbon - air/oxygen-mixtures.
The inhibition efficiency of these substances was evaluated by different test methods and different hydrocarbons were used also. Unfortunately there was no substance, its inhibition efficiency being evaluated by all methods used. Being aware that a comparison of the test results obtained with different test methods can be affected with a fault, it was tried nevertheless to compare the inhibition efficiencies gained. [3].
In Table 1 the inhibition efficiencies of chemical compounds are shown.
For the comparison the inhibiting efficiency of CCl_4 (Carbon tetrachloride) was chosen 1 and the efficiencies of the other substances was expressed by the ratio of efficiency of the substance to that of CCl_4.
From the various compounds tested, only a few like the halons 1301 (CF_3Br) and halon 1211 ($CF_2Br\,Cl$), the dry powders K_2SO_4, $KHCO_3$ and still $NaHCO_3$ and CO_2 and N_2 are used as fire extinguishing agents.
The extinguishing efficiency of halons and dry powders is attributed to an inhibition of the combustion reaction via chain breaking in the gaseous phase or on the solid walls of the powder particles respectively. While there is a lot of agreement on the inhibition mechanism of the halons, the possible reaction mechanisms leading to an inhibition of the combustion reaction of hydrocarbon-air mixtures by dry powders are still discussed.
For the extinguishment of quasi three dimensional fires, following a crash of an airplane only halon 1211, and the dry powders on K_2SO_4 and $KHCO_3$ basis are suited best. Halon1211 is more effective than the two dry powders. It also prevents reignition of the already extinguished fuel for a limited time, depending on the amount of halon used for extinguishment.
From the test results obtained with K_2SO_4 and $KHCO_3$ one can conclude, that these dry powders do not differ much in their extinguishing efficiency. There is some evidence that

with increasing fire sizes K_2SO_4 powder is more effective than $KHCO_3$. Therefore further more detailed studies should deal with the influence of the size of the fire, the influence of the extinguishing equipment used and the nozzle geometry on the extinguishing efficiency.

Extinguishing agents for quasi two dimensional fires

For the extinguishment of quasi two dimensional fires, nouncly the pool fires following a crash in the presents of reignition sources,extinguishing foams are the only adequate extinguishing agent today.
The extinguishing mechanism of foams is mainly due to the separation of the reactive species fuel and oxygen by a closed foam blanket. Furthermore the water released by the foam cools the fuel surface. For completeness it should be mentioned that the water vapor which is formed at the interface between the foam and the flame may also contribute to the extinguishment via a change in the fuel oxygen ratio.
Extinguishing foams are described mostly by the foam forming agent used, the mixing ratio of foam forming agent and water, the expansion ratio and the drainage time (25 % or 50 %).

Four different types of foams are in use today: protein foam, fluorprotein foam, synthetic foam and aqueous film forming foam (AFFF-foam) depending on the nature of the foam-forming agent. All foams can be employed as low expansion foams, AFFF and synthetic as medium expansion and high expansion foams too. (With expansion ratio of a foam ratio air to water is denoted.)
For the extinguishment of large fuel spill fires only low expansion foams are used. The tests described in this paper were - if not mentioned especially - all carried out with low expansion foams.
The extinguishing efficiency of the foams depends on the type of foam forming agents. Comparing the relevant foams to a preselected application rate, the shortest extinguishing times were achieved with AFFF foam like Light Water. Fluorprotein foam follows in efficiency. Synthetic foam proved to be less effective than fluorprotein foam and Light Water. The worst results were obtained with protein foam. For fundamental studies a foam from a mixture of Light Water and protein foaming agent was used too. Although this foam came off best, it is believed to be of no importance for practical use. The high efficiency is only achieved under very specific conditions and it is doubtful, if these conditions can always be adjusted. Figure 1 shows the test results for a 2oo m^2 pool and Figure 2 for the 0,1 m^2 pan. In these figures the extinguishing time is plotted against the application rate.
As can be seen from the figures too the extinguishing time depends also on the application rate of the foam. With increasing application rates the time needed for extinguishment decreases. Application rates greater than 7 to 10 $l/m^2 \cdot min$ (depending on the type of foam forming agent) lead to no further decrease in extinguishing time. The amount of foam which is applied in the unit of time can not spread in this time, hence a for the extinguishment of the fire unnecessary thick layer of foam is produced.
On the other hand, no extinguishment is achieved, if the application rate subsides below a critical value. This application rate is called the critical application rate. The critical application rate is different for each type of foam. An extrapolation of the curves in Figure 1 gives the following critical application rates for the four types of foams: Light Water 0,8 $l/m^2 \cdot min$, fluorprotein foam 1,3 $l/m^2 \cdot min$, synthetic foam 2,6 $l/m^2 \cdot min$ and protein foam about 4 $l/m^2 \cdot min$. The critical application rate depends mainly on the foam forming agent. The size of the burning fuel surface seems to be, if there is a dependence of minor influence on the critical application rate, at least between burning areas from 0.1 m^2 to 500 m^2.
The critical application rate is of high importance for the practice. Mostly the number and the capacity of crash tenders available are fixed and with this the maximum possible application rate. Under these conditions, the size of the fire which can be extinguished depends only on the foam forming agent used. For example, Table 2 shows the results of tests in which the maximum size of burning fuel surface was evaluated which could be extinguished

with a 200 l/min foam nozzle.

Normally the foam is applied locally to the fuel surface by hand branch pipes or monitors. From these points the foam has to be spread under the action of the gravity force in order to form a closed foam blanket.

The following figure (Figure 3) shows the spreading behaviour of the foams. In the figure the flow-time is plotted versus the distance the foam has propagated during that time. It can be seen from the figure that Light Water, an AFFF-foam, spreads most rapidly, followed by fluorpr.tein foam and synthetic foam. Protein foam exhibits the worst spreading behaviour.

Foams in general are media of high viscosity. Therefore the spreading of the foam is governed by the foam viscosity. In the next figure (Figure 4) the viscosity of the foam is plotted versus the time the foam needs to propagate a given distance. As could be expected the foam with the lowest viscosity (Light Water) has the highest spreading velocity and vice versa (protein foam). That means that Light Water will form a closed foam blanket in the shortest time, while protein foam needs the longest time to achieve the same results. As also can be seen in this figure, the different foaming agents lead to foams with different viscosities.

Since viscosities play a major role in the spreading of foams, one should expect, that a correlation between the viscosity of the foam and extinguishing time is existing. In the next figure (Figure 5) the extinguishing time is plotted against the viscosity of the used foams. The lower the viscosity of the foam, the higher is the spreading velocity of the foam, and with that less time is needed to form a closed foam blanket, a requirement for the extinguishment.

Besides the influence of the foam forming agent on the foam viscosity, the viscosity - within certain limits - also depends on the energy used to form the foam from the water foaming-agent solution. The more energy is put into the foam, the more viscous, the stiffer the foam becomes. Beyond a certain amount of energy input the viscosity of the foam remains constant. (Figure 6) In this figure the number of sieves in the mixing chamber is chosen as a measure for the energy input. The number of sieves is correlated to the energy input by the pressure loss caused by them. This foaming energy dependence of the viscosity must have its reflection on the time needed for extinguishment. In Figure 7 the extinguishing time for AFFF-foam is plotted against the viscosity of the foam. The viscosity is expressed by scale units. The time needed for extinguishment is the longer, the more energy was used to foam the water foaming agent solution. This energy dependence of the foam viscosity is one of the causes of different extinguishing efficiencies of foam monitors or branch pipes. Monitors and branch pipes of different manufactures deliver foams with different viscosities. [4].

It is also one of the reasons, why an AFFF foam has a higher extinguishing efficiency when applied with a non air-aspirating nozzle. (The other factors are discussed in detail later on in this paper.)

The expansion ratio of the foam also influences the extinguishing efficiency of a foam. Test results, obtained with medium expansion foams (expansion ratio 68) on a 200 m^2 pool, give evidence that with these types of foams shorter extinguishing times can be achieved. (Figure 8) Although the fuel fire could be extinguished with the low expansion foam in a shorter time, the use of medium expansion foam for post crash fire fighting can not be recommended for two reasons. The throw range of medium expansion foam nozzles is too short, just a couple of meters. Wind velocities exceeding 6 to 8 m/sec make it impossible to cover the whole fuel surface with a foam blanket. The specific weight of the foam is too low. As a consequence the foam is blown away by the wind. Wind velocities of this magnitude can not be excluded on an airport. Hence only low expansion foams can be used for crash fire fighting. In Figure 9 the correlation between expansion ratio and extinguishing time in the range of an expansion ratio from 0,1 to 40 is shown for Light Water foam. With Light Water foams of an expansion ratio under 0,5 a fuel fire can not be extinguished. The extinguishing efficiency increases rapidly with the expansion ratio between 0,5 and approximately 1 to 1,5. Expansion ratios between 1,5 and 10 have no reflection on the extinguishing efficiency. With increasing expansion ratios over 10 the extinguishing time of the Light Water foam decreases. Most of the monitors and hand branch pipes for low expansion foam produce foams with expansion ratios between 4 and 8.

For completeness it should be mentioned that the concentration of the foam forming agent is also of influence on the extinguishing time [5]. (Fig. 10) In this figure the extinguishing time is plotted versus the concentration of an AFFF foam forming agent in the water-foam forming agent solution. The extinguishing time decreases rapidly with the increasing foam forming agent concentration from endless (no extinguishment) to a minimum value in a concentration range from 0 to 1 percent. For foam forming agent concentration from 1 to 5 percent this value is nearly independant of the concentration. This correlation is explainable. The surface tension of a water-foam forming agent solution is a function of the concentration of the foam forming agent. (Figure 11) As can be seen from this figure the surface tension of the solution exhibits the same tendency as the extinguishing time, a result which could be expected because of the correlation between surface tension - foam viscosity, spreading velocity and extinguishing time.

The concentration recommended by the manufacturer for this foam forming agent is 3 percent. The concentration of the foam forming agent can vary between 2 to at least 5 percent, without changing the extinguishing efficiency of the foam.

From the dependence of the extinguishing efficiency on the concentration of the foam forming agent in the water-foam forming agent solution the requirements on the accuracy and reliability of mixing units can be deduced.

The foaming agents reduce the surface tension of the water-foaming agent solution, a requirement for the formation of foam. The foaming agents differ in their ability to reduce the surface tension. With the exception of the Light Water-Protein mixture, Light Water shows the highest reduction of the surface tension, followed by fluorprotein and synthetic foam agents. Protein-based foaming agents are less effective. The surface tension of the water-foaming agent solution influences the viscosity of the foams formed from the solution. From solutions with low surface tensions low viscosity foams are produced. The higher the surface tension, the higher the foam viscosity becomes. The correlation between surface tension of the solution and the foam viscosity is shown in Figure 12.

From the discussed test results one can assume, that the extinguishing efficiency of foams is proportional to the velocity with which a closed foam layer is achieved on the fuel surface. This velocity is a function of the foam viscosity. The foam viscosity itself depends on the surface tension of the water-foaming agent solution and can be influenced to a certain extend by the energy used to foam the water. From the correlations between surface-tension, foam viscosity and extinguishing time one may derive the conclusion, that a further pronounced increase in extinguishing efficiency of the presently used foams cannot be expected.

Extinguishing efficiency of halon foams

The extinguishing efficiency of water-air foams can be increased by an addition of halons to the water. When a liquid halon such as halon 1202, 2404 and halon 1211, although the boiling point of this halon being 4 ^{o}C, is mixed to the water-foaming agent solution, and the solution is foamed in the usual manner with air, an increase in extinguishing efficiency can be registered in a limited range of halon concentration. The results of extinguishing tests with synthetic foaming agent and fluorprotein foaming agent are shown in Figure 13 and in Figure 14 for Light Water foaming agent. The sequence of effectiveness of halon foams is again Light Water, fluorprotein foam and synthetic foam. In Figure 15 the

extinguishing efficiency of Light Water-halon 1211 foams with various halon concentrations in the solution is shown. The extinguishing time decreases with increasing halon concentration, with a flat minimum between 10 to 30 percent of halon in the solution. Halon concentrations over 30 percent cause longer extinguishing times again and halon foams with a concentration of 50 percent halon and more in the solution have no extinguishing effect at all. The specific weight of the foam is bigger than that of the fuel. As a consequence the foam submerges under the fuel surface. The extinguishing efficiencies of halon 1202 and 2402-Light Water foams are of the same order.
From the point of view of extinguishing efficiencies only Light Water-halon foams can be recommended for practical use. From the toxicological point of view halon 1211 should be prefered. The halon 1211-Light Water foam is known under the name Nêvê. The extinguishing efficiency of Nêvê with respect to the other foams is shown in the first two figures. Although the extinguishing mechanism of the halon foams is not yet understood completely, it can be assumed that a chemical interaction of the halons with the burning reactions may be of importance. Halons are known as very effective inhibitors of the hydrocarbon-oxygen reaction. If this is the main reason for the increase in efficiency, Nêvê and the halon 1202 and 2402 Light Water foams would be the foams with the highest efficiency that could be expected.

For the formation of foam from the foam forming agent water solution commonly air is used. The use of other gaseous medias instead of air were under discussion in order to increase the extinguishing efficiency. The nature of the gas contained in the foam bubbles has no influence on the extinguishing efficiency. Figure 16 shows the test results with Light Water foams. The water-Light-Water solution was foamed with gaseous halon 1301 and carbon-dioxide respectively. For comparison the results for Light-Water-air foam are plotted in the figure too. This may be attributed to the fact that the halon concentration in those foams containing a liquid halon is by a factor of 4 higher than in the case described in Figure 16. In order to get better throw ranges it was proposed recently that the foaming of the solution should take place first on the fuel surface under the influence of the heat produced by the flame. By choosing halons with adequate boiling points this is possible. However all tested mixtures were less effective than Nêvê.

Influence of the size of the burning fuel surface on the extinguishing time

The extinguishing tests, described in the previous chapters, were carried out on fuel surfaces ranging from 0,1 m^2 to 500 m^2. If one relates the time needed to extinguish the burning fuel surfaces to the size of surfaces, that means the time needed to extinguish the unit of burning area $\frac{sec}{m^2}$, which shall be called specific extinguishing time, one gets a correlation between the specific extinguishing time and size of burning fuel area for a given application rate as shown in Figure 17 for Light Water, application rate 1 and 5 $l/m^2 \cdot min$ and for fluorprotein foam, application rate 1,3 $l/m^2 \cdot min$.
In the figure the values are plotted on a logarithmical scale. In the range of burning areas between 0,1 m^2 and 100 to 200 m^2 the specific extinguishing time decreases lineare-ly with the burning area. In figure 18 the same is shown in more detail for Light Water [6]. Tests carried out with toluene [7] lead to a similar correlation (Figure 19). For larger burning areas the linear correlation must change. This is plausible, because otherwise the extinguishing time would become zero at very large burning areas. In the literature only four results of tests on larger areas than 500 m^2 were found on which could be made full use of. Unfortunately the burning areas differed only by a factor of four and five, hence a reliable extrapolation of the datas to larger fire surfaces seems not possible, presently. Therefore it is intended to carry out extinguishing tests on 5000 and 10 000 m^2 pools in order to complete the correlation.
Burning areas of this size are of interest to the oil industries.

Influence of the fuel on the extinguishing efficiency of foams

The fuel which is to be extinguished has also an influence on the extinguishing time. From the available test datas one can conclude that the boiling temperature and the viscosity of the fuel influences the extinguishing time. Figure 20 shows the dependance of the extinguishing time on the boiling temperature or vapour pressure of the fuel. For these tests Butane, Pentane, Hexane, Heptane, Dodecane and Tetradecane were used as fuels. From that figure it can be seen that the lower the boiling temperature or the higher the vapour pressure of the burning fuel the more time is needed to extinguish the fire. From this correlation follows that the fuel temperature must also have an influence on the extinguishing time. In Figure 21 the extinguishing time is plotted against the fuel temperature before ignition. In these tests Heptane was used. As could be expected the extinguishing time increased with the fuel temperature.

The spreading velocity of a fluid is not only depending on the viscosity of the fluid itself but also on the friction between the fluid and the surface on which it flows or spreads. As already mentioned, foams are media of high viscosity. Their viscosity is normally higher than that of the fuel which is to be extinguished. The velocity with which the foam spreads on such surface therefore also depends on the viscosity of fuel.
Due to the friction forces secondary flows in the fuel are induced. The higher these velocities are, and that means the lower the viscosity of the fuel is, the faster the foam spreads on the surface of the fuel. In Figure 22 the extinguishing time for Diesel fuel is shown as a function of the viscosity of the fuel. The viscosity of the fuel was changed by adding different amounts of an inort fuel thickener, in this case SiO_2. The maximum amount of thickener adds was about 1 % by weight. For the tests with a Diesel fuel with a solid surface another kind of thickener was used.
The extinguishing time increased with the viscosity of the fuel and reached for the solid Diesel fuel a value, which is nearly three times higher than that of the unthickened fuel. This dependance of the extinguishing time on the viscosity of the fuel may have its reflection on the extinguishment of antimisting fuels. To our knowledge, no extinguishing-tests using antimisting fuels have been carried out until now.
Fuel may also be spilled on soil, without forming a concrete fuel surface on which the foam can spread during extinguishment, a condition similar to that of the solid fuel. On such a surface the foam spreads considerably slower, as shown in Figure 23 for fuel soaked sand. Therefore the extinguishing time must be longer. In Figure 24 the test results obtained with Light-Water on fuel soaked sand are given.

Extinguishing tactics

The distance, a foam has to be spread under gravity forces on the fuel surface which is to be extinguished in order to form a closed foam blanket is - besides the foam properties - another governing factor that influences the time needed for extinguishment, as can be seen from Figure 25. In this figure the extinguishing time/foam application rate dependence is shown for a circular and a rectangular pan. Also the following test results obtained with Light-Water on a 50 m^2 pool illustrate this. The extinguishments were carried out with an application rate of 5. No extinguishment after 5 minutes of foam application was achieved, when the foam was applied through the flames to a hot iron plate adjusted opposite the monitor on the other side of the pool. Four minutes were necessary to extinguish the fire, when the foam monitor delivered the foam on one edge of the pool. The extinguishing time was reduced to two minutes when the foam monitor just turned during extinguishment without changing position. The extinguishing time decreased by a factor of two, when the foam was placed on the fuel surface in the vicinity of the interface between the flame and the already extinguished part of the fuel surface. This extinguishing technic requires that the foam monitor follows the retreating flame and sweeps at the same time. With a full foam jet the extinguishment needed 48 seconds, with a slightly dispersed jet the fire was out after 53 seconds of foam application. The extinguishing times differ only by 10 %. Therefore some further studies should deal with the evaluation of best foam jet configuration.

Water nozzles display higher throw ranges than comparable air aspirating nozzles. This is in view of short flow distances of the extinguishing foam of advantage for obtaining short extinguishment times. Therefore it was tried to test water nozzles on their ability for the extinguishment of fuel spill fires a field of application for air aspirating nozzles.

By use of non air aspiration nozzles the exquishing times could be reduced about 20 % and more [8], under the conditions of same application rate. Non air aspiration nozzles which work with a water-AFFF foam forming agent solution - other solutions have not been tested - produce also a foam with an expansion ratio of approximately 1.9 and more, depending on the spray pattern of the water foam solution jet. The extinguishing efficiency is in a range beginning with expansion ratios about 1 to at least 7 or 8 independent on the expansion ratio, if care is taken that the viscosity of the foam with the different expansion ratios is kept constant. AFFF-foam produced with the non air aspiration nozzles had a lower viscosity than that from an air aspiration nozzle, as the tests carried out have shown. (Further tests will have to prove if this is a general fact.)

The extinguishing efficiency depends on the foam viscosity as already discussed (Figure 26). The results of the extinguishing tests with non air aspirating nozzles are in correspondence with those test results. The non air aspirating nozzles used in the tests produced a foam with AFFF-foam forming agent on the fuel surface, with an expansion ratio which is in the range of a low expansion foam, where the extinguishing efficiency is independent of the expansion ratio. The viscosity of this foam is lower than that of equivalent air aspirating nozzles. With that the extinguishing time should be shorter, as the tests proved.

Extinguishing efficiency of dry powder-halon-foam combinations

As already discussed, in a post crash fire quasi two and three dimensional fuel fires may occur and have to be extinguished. An optimum fire fighting of these fires is only possible when using a combination of three dimensional acting agents like halons or dry powders and a foam. On the extinguishing efficiency of halon- or dry powder-foam combinations and on problems arising from the use of the agents at the same time only little literature is available, and unfortunately some of them are confidential.
From the few test results, on which could be made full use of, one may conclude, that the time needed for extinguishment will be decreased when using a combination of dry powder, halon and foam.
The extinguishing efficiency of a combination seems to depend on the efficiency of the used different agents. The more effective both are, the shorter is the extinguishing time achieved in a combined use. The shortest extinguishing times were obtained, when a halon 1211-AFFF foam combination was used for extinguishment, followed by polassium sulphate-AFFF foam. The longest extinguishing times were needed, when the extinguishment was carried out with $NaHCO_3$ based powder and protein foam. The extinguishing times differed by a factor of approximately three. It has to be mentioned that this value may be a little inexact, because different equipments were used for the extinguishing tests.
A combined use of dry powder and foam is also profitable to a pool fire with reignition sources, as can be seen from Figure 26 and Figure 27. [9]. In these figures the heat radiation from the flame is plotted versus the extinguishing time. If the fire is extinguished with foam only (Figure 26), the heat radiation decreases with the time needed for extinguishment. Using a dry powder with the foam (Figure 27) the heat radiation is reduced immediately with the onset of dry powder application nearly to zero, except for the first seconds of powder application, where an increase in heat radiation was registered. This decrease in heat flux with the beginning of extinguishment may be of importance to the survivalability of the crew and passengers in the airplane.

Measurements of the conditions prevailing in a cockpit of a combat aircraft during extinguishment lead to this conclusion.
The use of dry powder with foam may also lead to shorter extinguishing times.
The time needed to cover a pregiven fuel surface with foam is shorter without the presence of a fire (that means in case of extinguishment), during the time needed for building up a closed foam blanket, foam is destroyed by the flames. Therefore the formation of the foam blanket takes more time than without a fire. (Figure 28)
In this figure the difference of time needed to cover the fuel surface with and without a fire is plotted versus the application rate of the foam. When using a dry powder in combination with a foam, the fire is at least partly extinguished for some time by the dry chemical, so that the foams can spread faster.

Foam monitors

An extinguishing technic with which short spreading distances are achieved, requires not only crash tenders that can maneuvre with the output of the full foam capacity during extinguishment. The foam monitors must also have an adequate through range. Foam losses between the monitor and the fire should be low. That requires jets which dissolve only at the end of the throw range.

Foam jets show the same characteristics as water jets in respect to the dispersion of the jet. [10]. The dependence of the break up of a jet depends on the Ohnesorge- and Reynolds-number. The foam jet configuration as a function of the Ohnesorge- and Reynoldsnumber is shown in Figure 29.

Foam monitors and hand branch pipes used for crashfire fighting produce foam jets which have Ohnesorge- and Reynolds-Numbers which lie in the range of dispersed jets. The degree of dispersion can be influenced to a certain extend by the geometry of the monitor.
The requirements for the mentioned monitors were fulfilled best by a monitor of a straight contraction, the cone angle being about 6 degrees to 12 degrees. They are objects to optimization in respect to the influence of the viscosity of the foam on the cone angle. Also the optimum radius of the effluence aperture has to be evaluated.

Conclusions

Many substances exhibit an inhibition efficiency of the hydrocarbon-air reaction. From these substances only the dry powders based on $KHCO_3$, K_2SO_4 and the halon 1211 are of interest for the fire fighting of quasi three dimensional fires arising after a crash.

For the extinguishment of quasi two dimensional fires, foams are used. From the test results described in this paper one can conclude that the extinguishing efficiency of foams is mainly influenced by the following properties: surface tension of the foam forming agent-water solution, viscosity of the foam and spreading velocity. These properties are not independent on each other. The lower the surface tension of the foaming agent-water solution, the lower is the viscosity of the foam produced by this solution. The viscosity of the foam fixes the spreading velocity of the foam.
Foams of low viscosity spread faster. They form a closed foam blanket in a shorter time. Accordingly shorter extinguishing times are achieved.
The viscosity of the foams and consequently the spreading velocity and the extinguishing time can be varied within certain limits by the energy which is used to foam the solution. The higher the energy input the more viscous the foam becomes.
Therefore foam monitors are more effective when producing foams with low viscosities, the main assumption for the superior extinguishing efficiency of non aspirating nozzles.

For the extinguishment of crashfires only low expansion foams can be used. Wind velocities above 6 to 8 m/sec make it impossible to produce a closed foam layer on the burning fuel surface.
The extinguishing efficiency of the foams can be improved by adding a fluid halon and also halon 1211 to the water-foaming agent solution. The best results were obtained with

halon 1211, 1202 and 1402-Light Water foams. The efficiency of these foams differ not substantially.
The fuel which has to be extinguished, also influences the extinguishing time. In respect to extinguishment the main properties of fuels seem to be the boiling temperature and the viscosity of the fuel. The lower the boiling temperature and the higher the viscosity of the fuel, the longer is the extinguishing time.
The time which is needed to extinguish the unit area of the burning fuel surface (the specific extinguishing time) is correlated to the size of the burning fuel surface, at least in the measured range of burning areas from 0,1 m^2 to 500 m^2. Further tests on larger burning areas are necessary.

The extinguishing technic also influences the time for extinguishment. The shortest extinguishment times are achieved with a tactic, whereby the distance the foam has to spread under gravity force is shortest. That requires foam monitors which have an adequate throw range. All foam monitors produce dispersed foam jets. The extend of dispersion can be reduced by the geometry of the foam monitor.
For the extinguishment of post crash fires, a combination of a dry powder or halon and a foam is necessary. Although some test results show, that the extinguishing efficiency obtained with a combined use of dry powders/halons and foams depends on the effisiency of the used agents, no concrete recommandation on the optimum combination of agents can be given.

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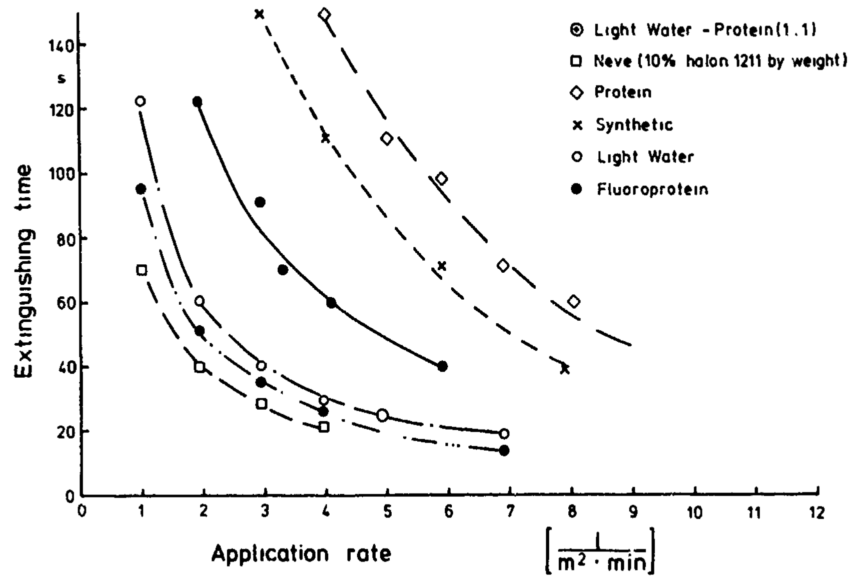

Fig. 1 Extinguishing time - application rate curves for low expansion foams (0,1 m^2 pan)

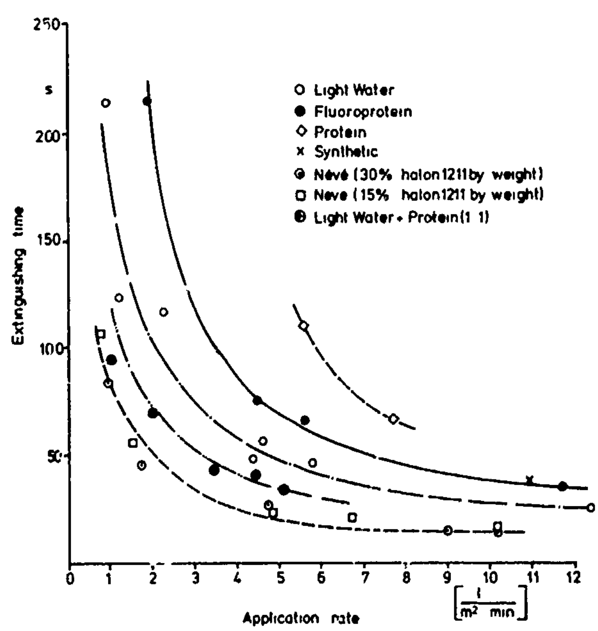

Fig. 2 Extinguishing time - application rate curves for low expansion foams (200 m^2 pool)

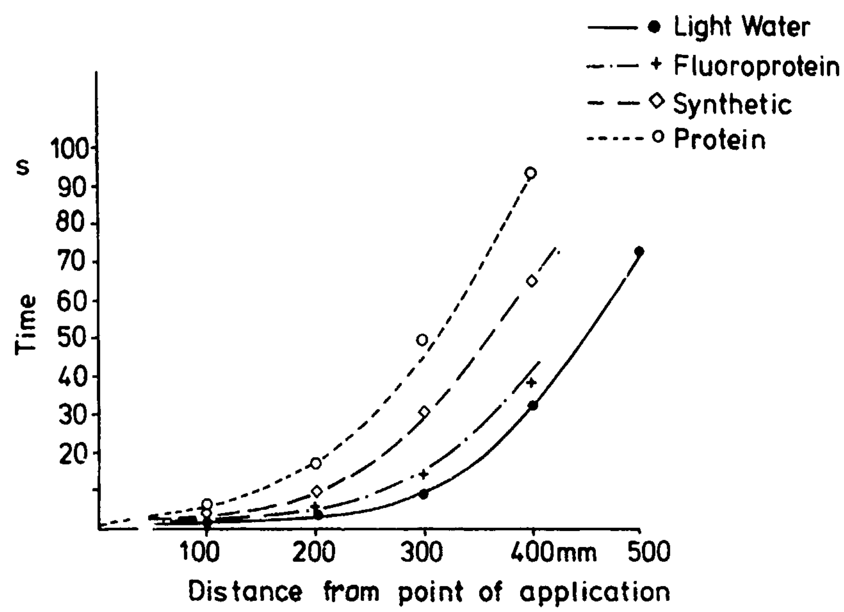

Fig. 3 Flow characteristics of foams on fuel

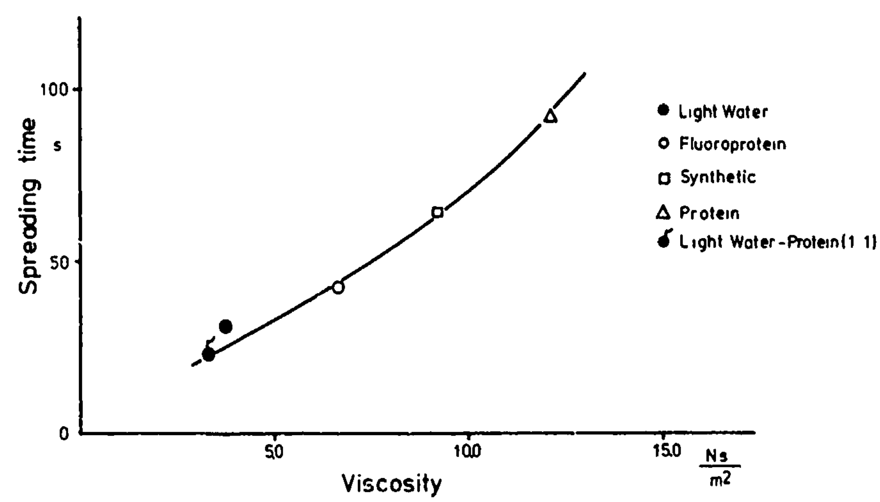

Fig. 4 Dependence of the spreading time on foam viscosity

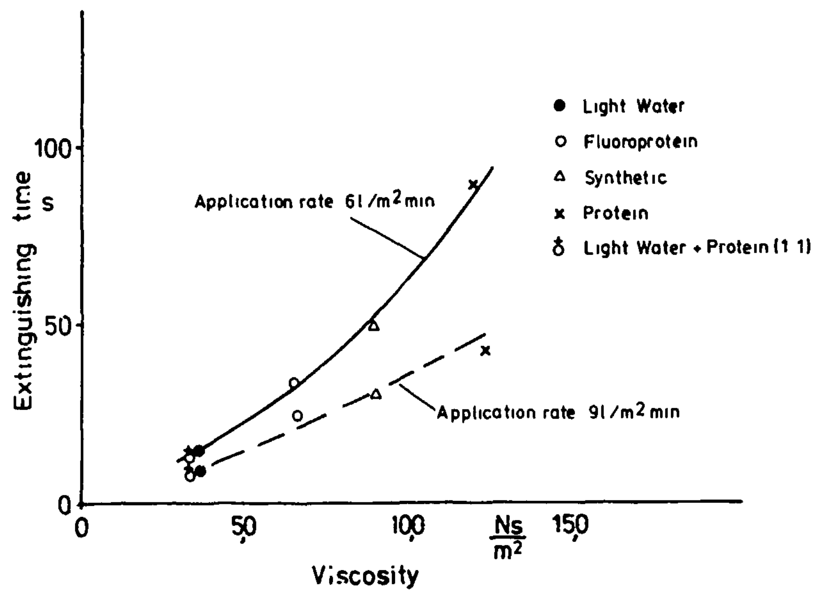

Fig. 5 Influence of the foam viscosity on the extinguishing time

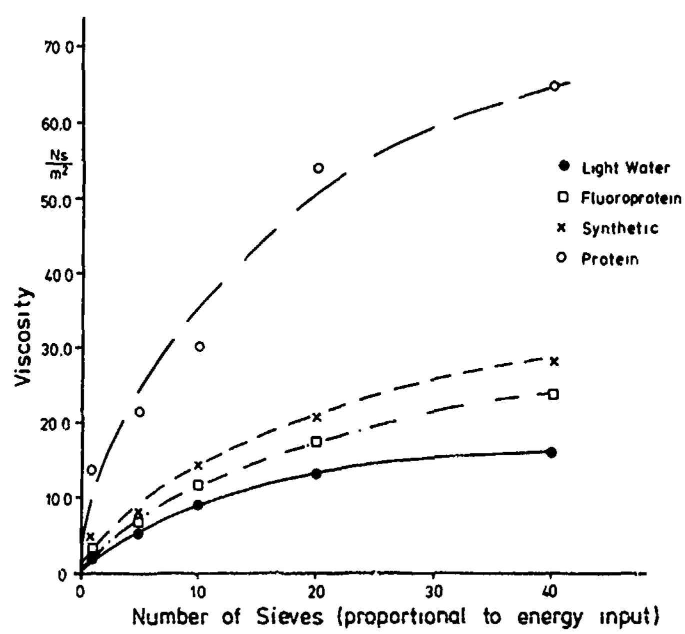

Fig. 6 Influence of energy used to produce the foam on the foam viscosity

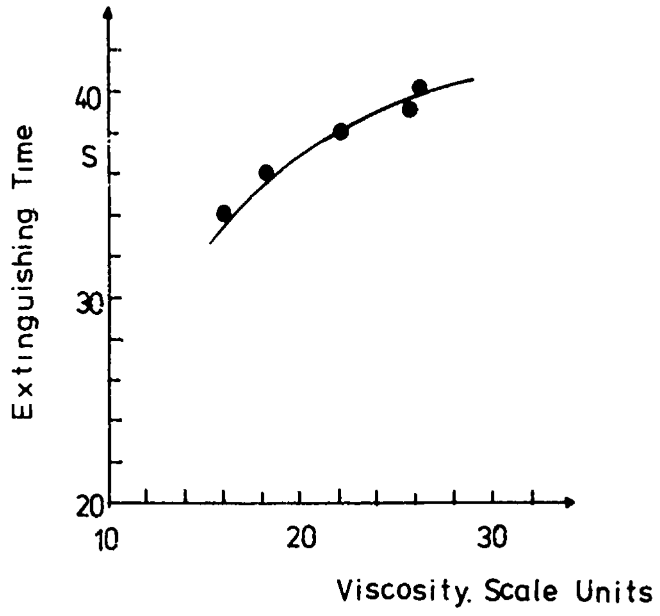

Fig. 7 Dependence of the extinguishing time of AFFF foam on the energy used to foam the solution

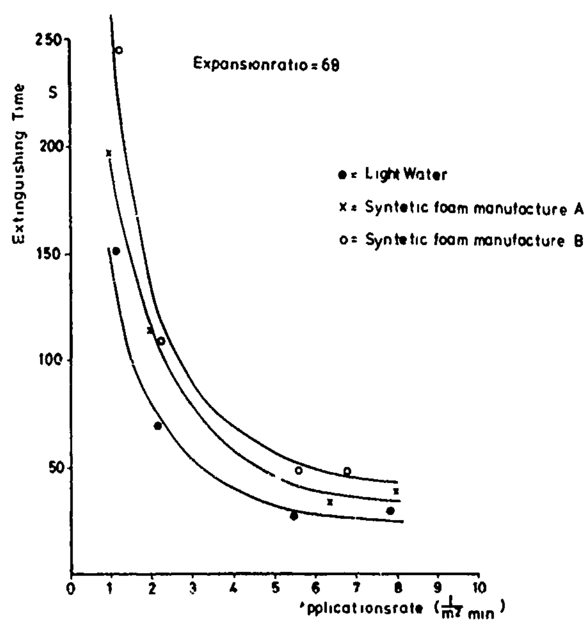

Fig. 8 Extinguishing efficiency of foams with medium expansion ratio

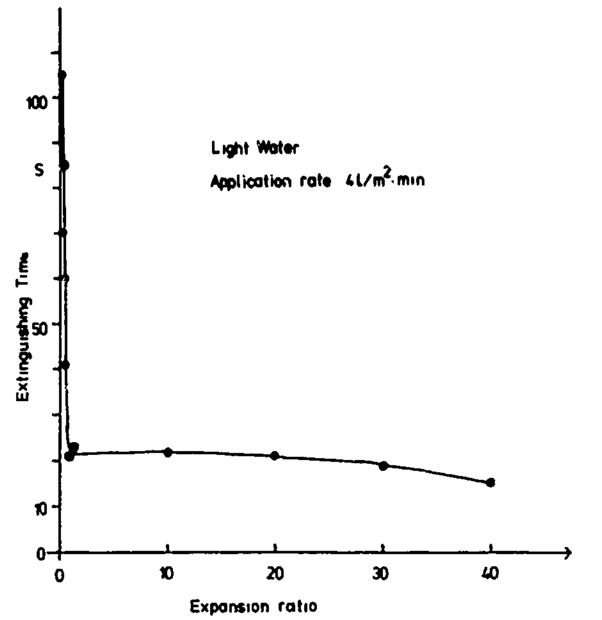

Fig. 9 Influence of the expansion ratio of the foam on the extinguishing time

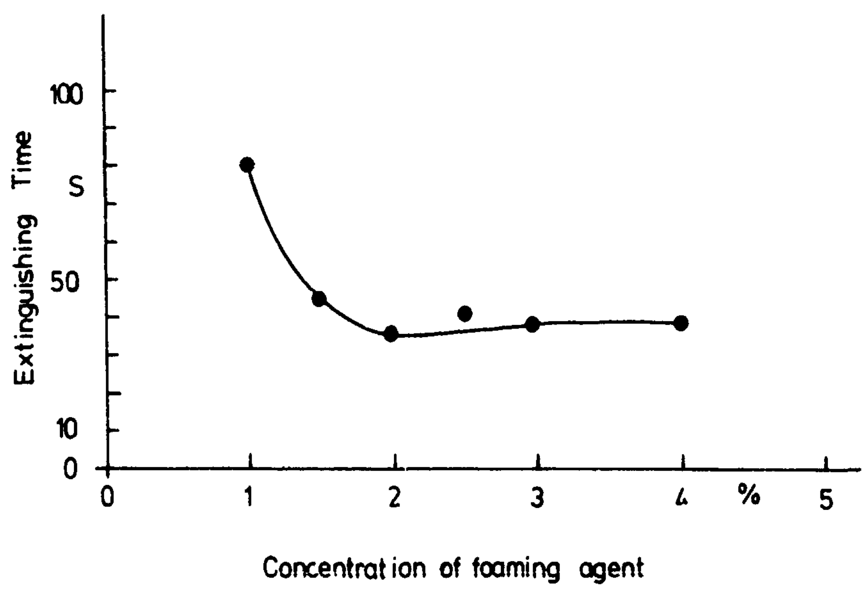

Fig. 10 Correlation between extinguishing time and the concentration of foaming agent (AFFF)

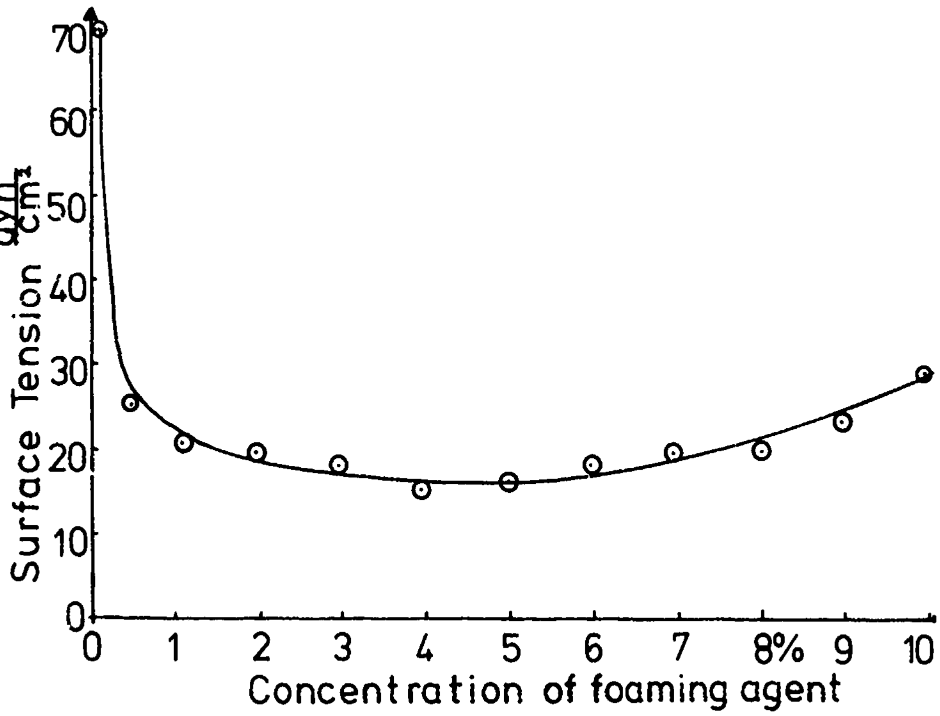

Fig. 11 Influence of the concentration of foaming agent on the surface tension of the solution.

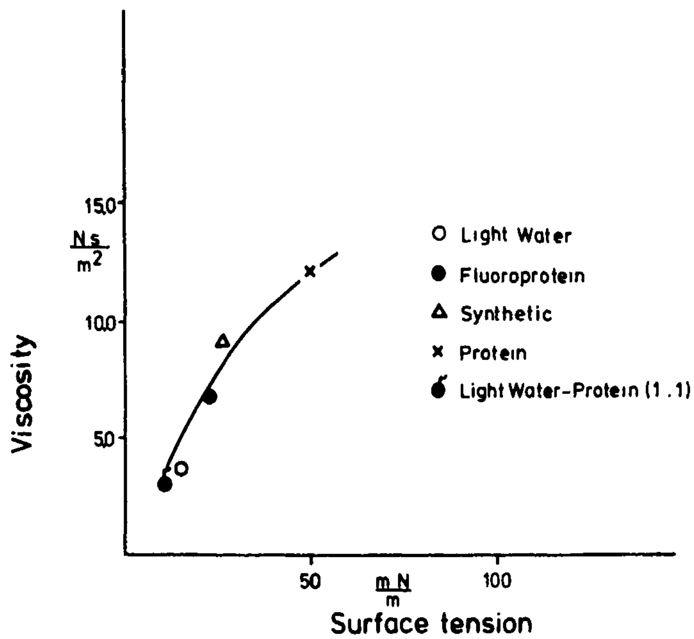

Fig. 12 Dependence of foam viscosity on the surface tension of the solution

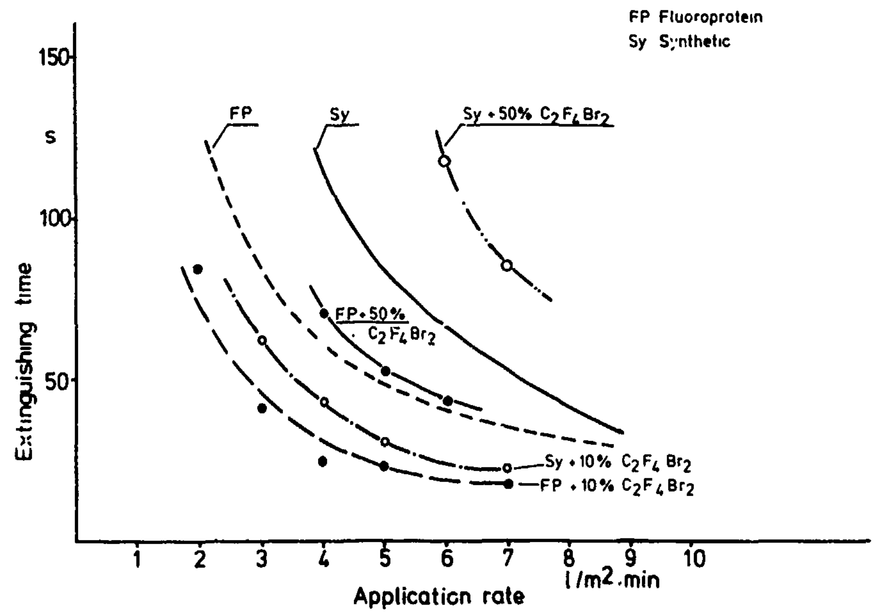

Fig. 13 Extinguishing efficiency of fluoroprotein - and synthetic - halon 2402 - foams

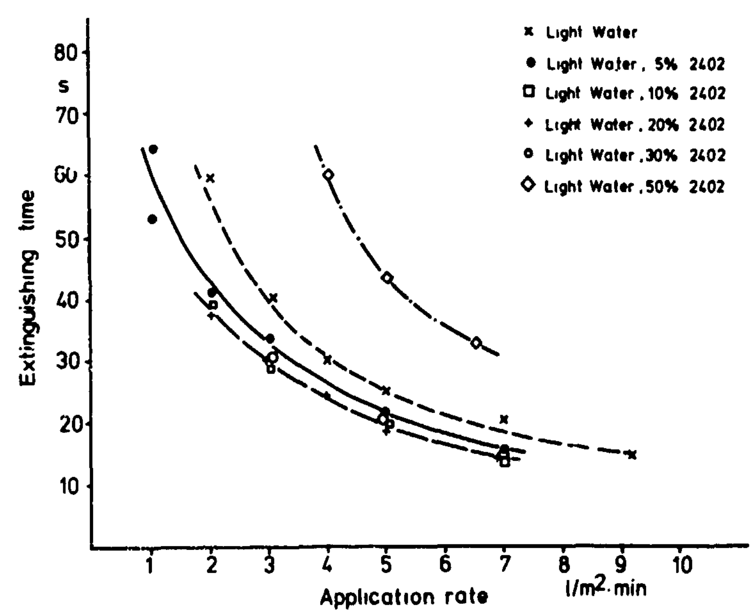

Fig. 14 Extinguishing efficiency of Light Water - water - air halon foam

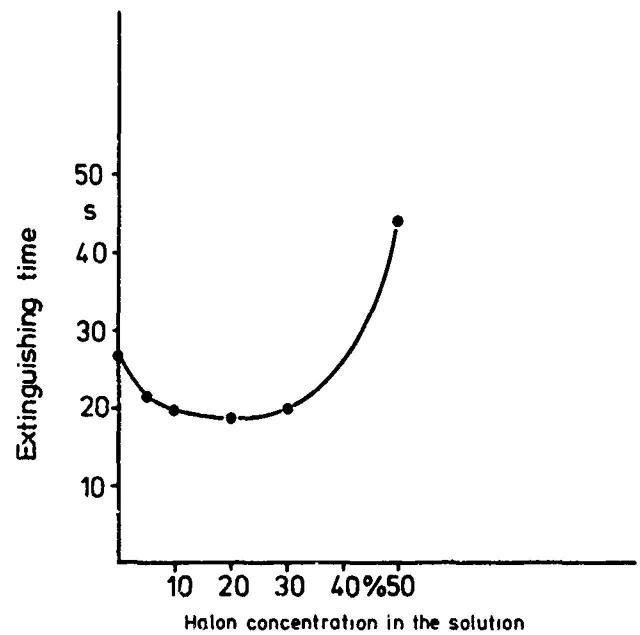

Fig. 15 Influence of the halon 1211 concentration on the extinguishing time of a Light water foam

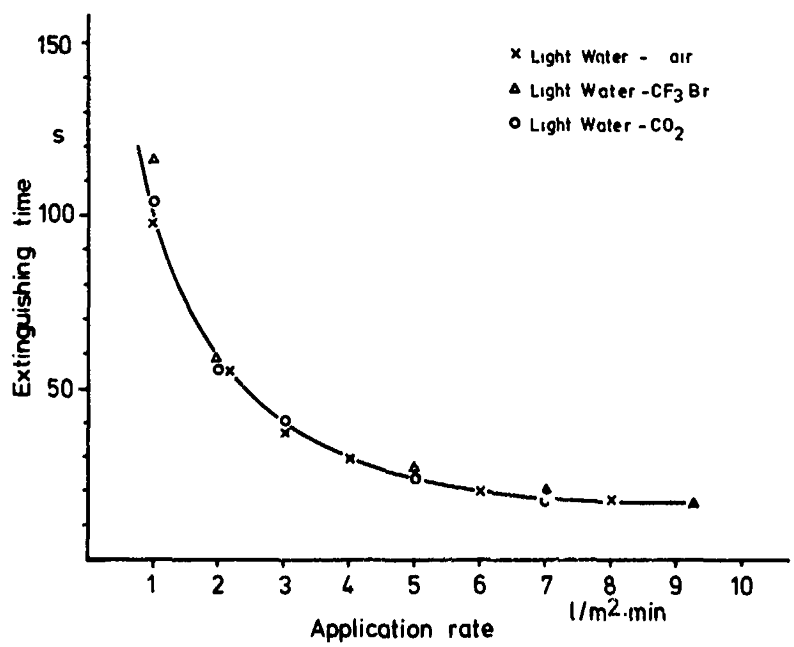

Fig. 16 Extinguishing time/application rate curve for Light-Water - water - air, CF_3Br and CO_2 - foams

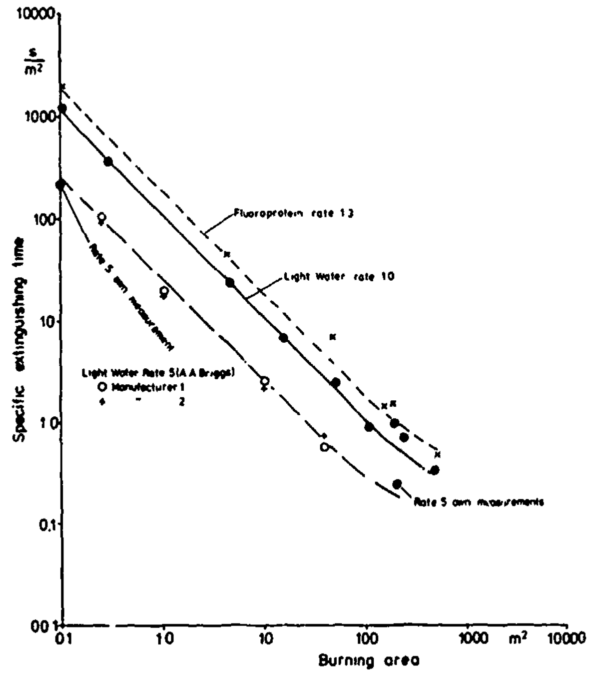

Fig. 17 Correlation between specific extinguishing time and burning fuel area for JP4

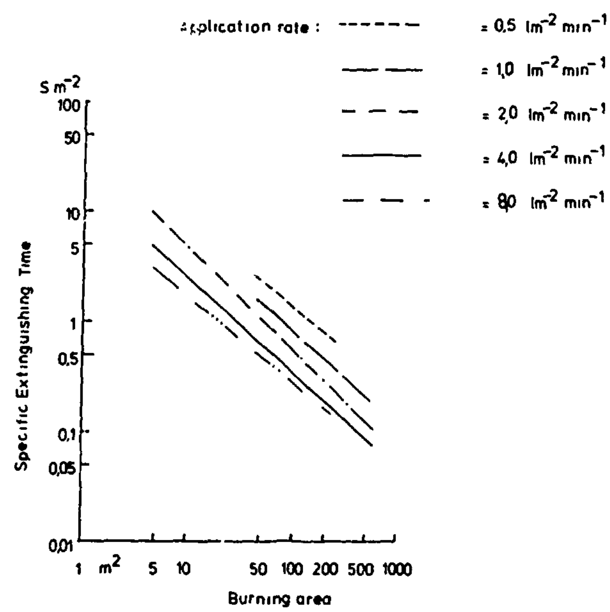

Fig. 18 Correlation between specific extinguishing time and burning fuel area for different applicacion rates of AFFF foam

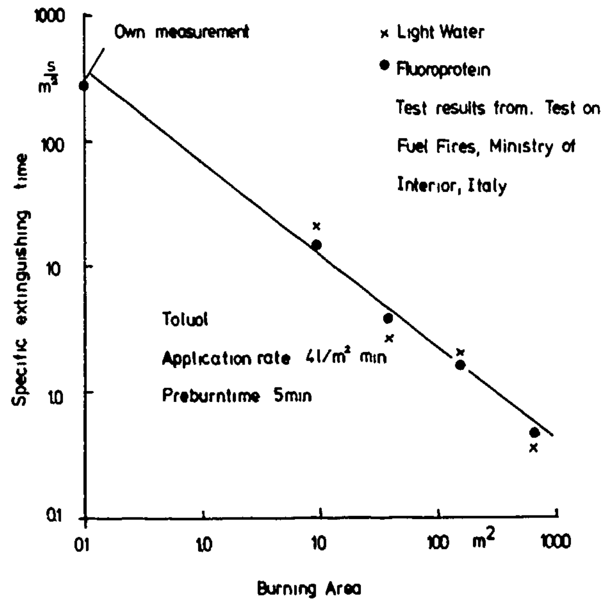

Fig. 19 Correlation between specific extinguishing time and burning fuel area for toluene.

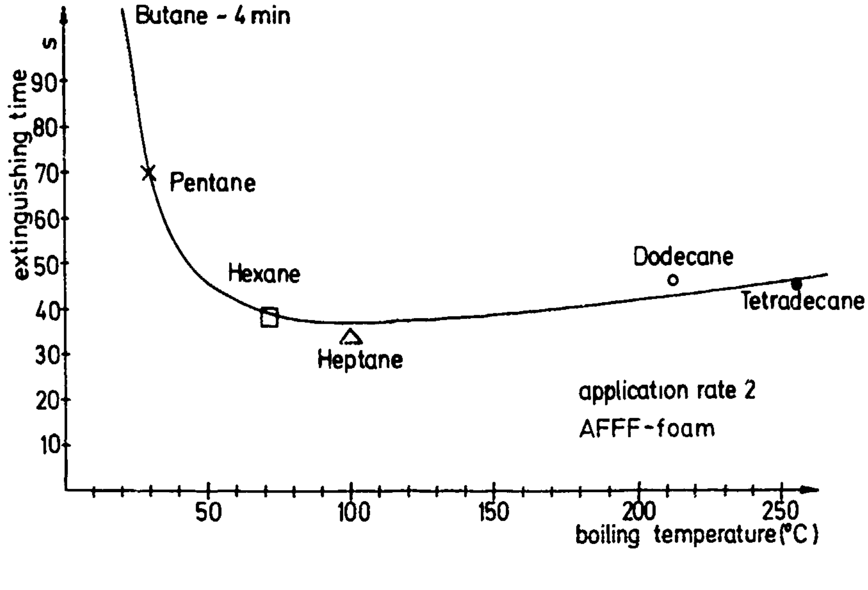

Fig. 20 Dependence of the extinguishing time on the boiling temperature of the fuel

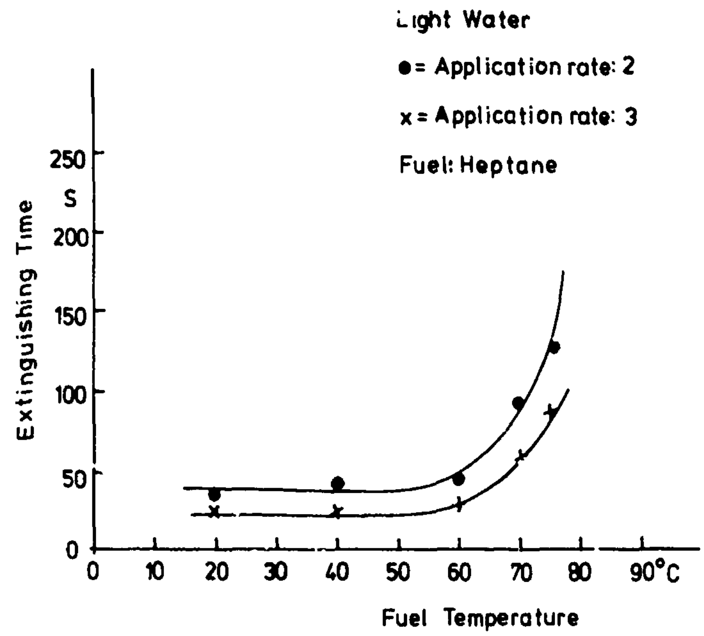

Fig. 21 Influence of the fuel temperature prior ignition on the extinguishing time

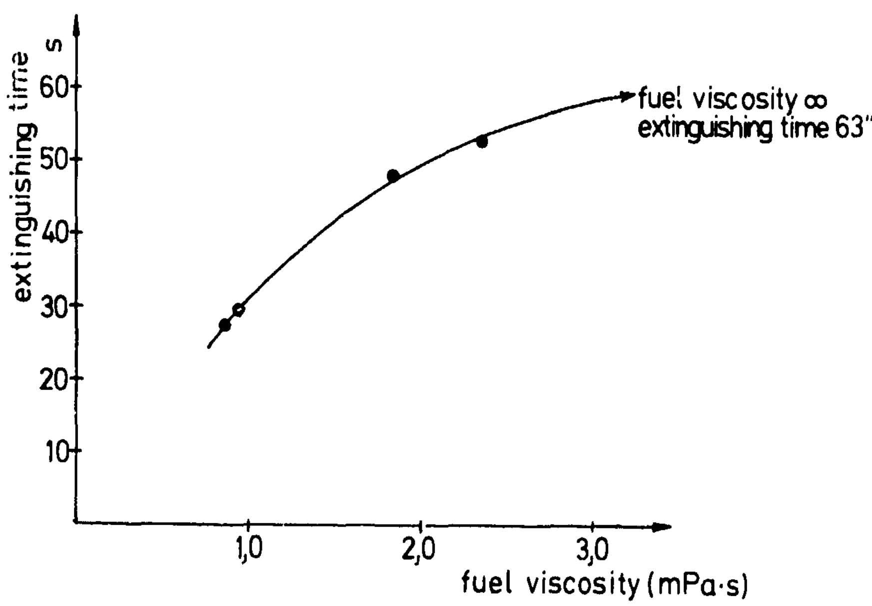

Fig. 22 Dependence of the extinguishing time on the viscosity of the fuel (Diesel fuel)

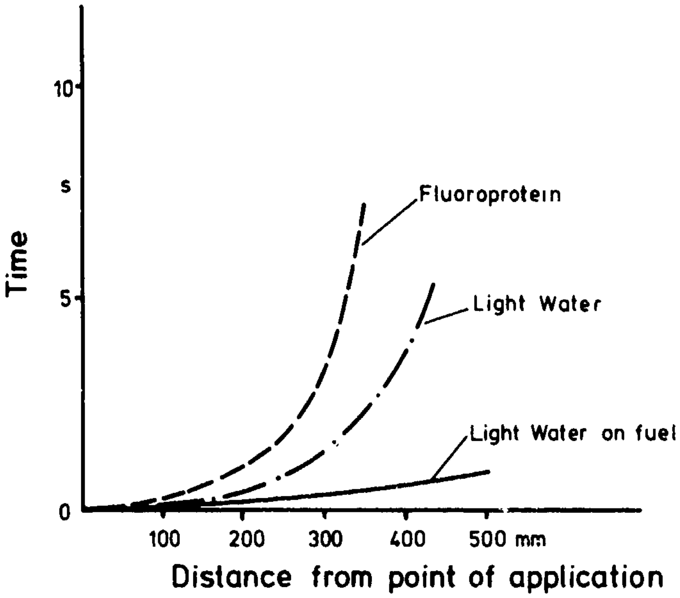

Fig. 23 Flow characteristics of foams on fuel soaked sand

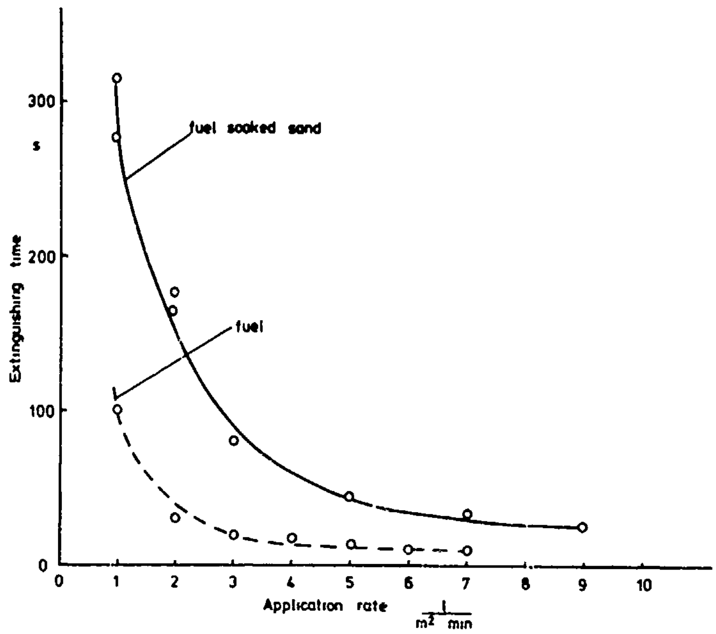

Fig. 24 Extinguishing time - application rate curve for Light Water for fuel soaked sand

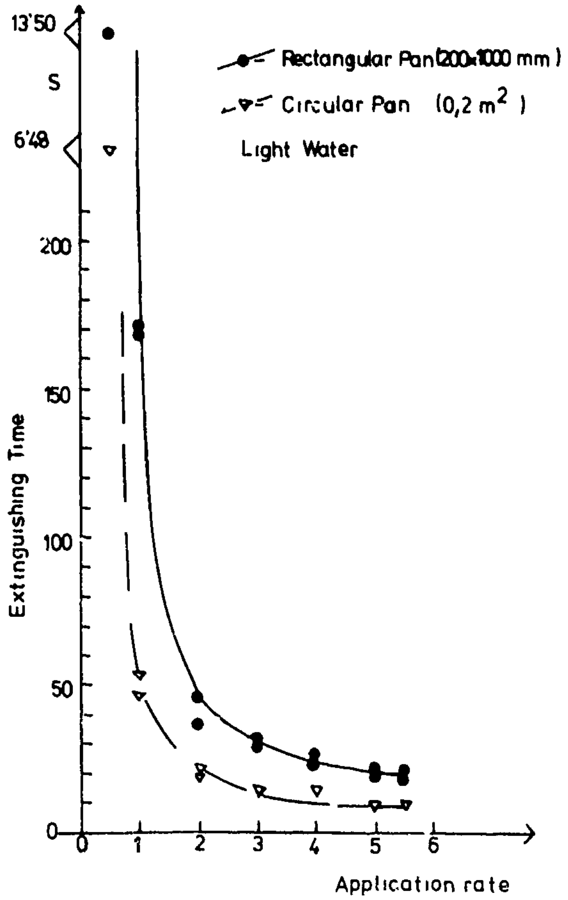

Fig. 25 Influence of the geometrie of the burning fuel surface on the extinguishing time

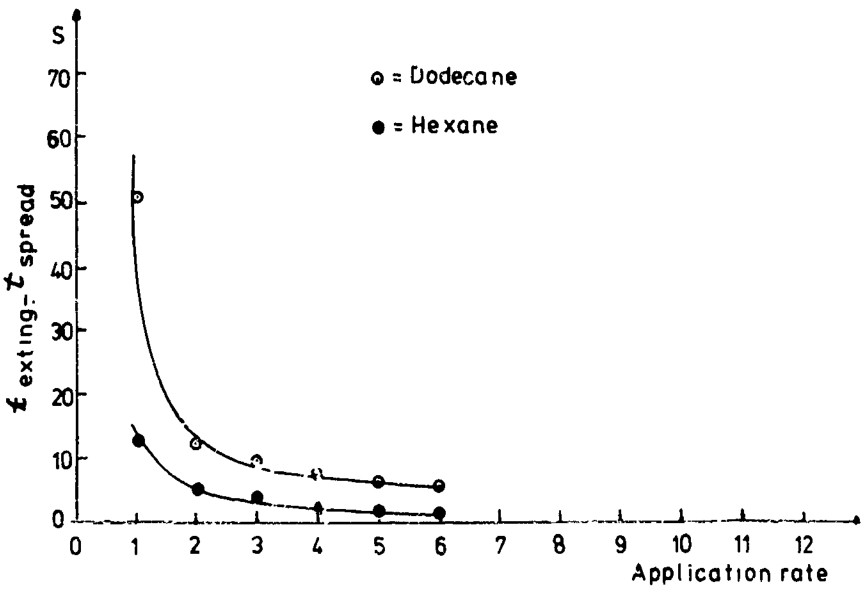

Fig. 26 Difference of extinguishing time and spreading time of AFFF foam on a fuel surface

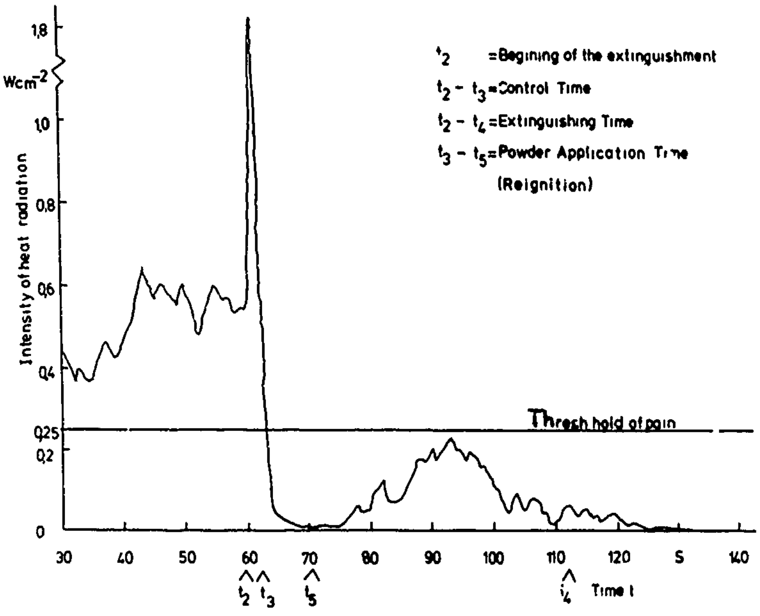

Fig. 27 Heat radiation from a flame during extinguishment with dry powder and foam

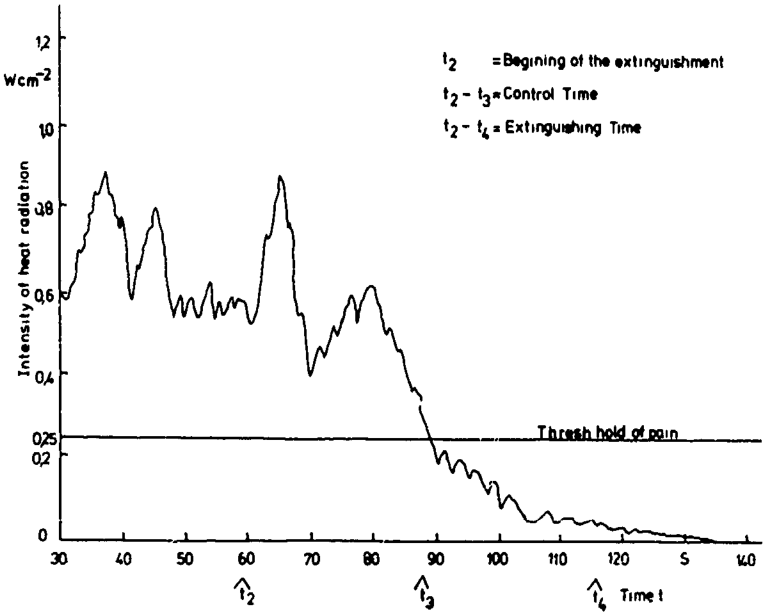

Fig. 28 Heat radiation from a flame during extinguishment with foam

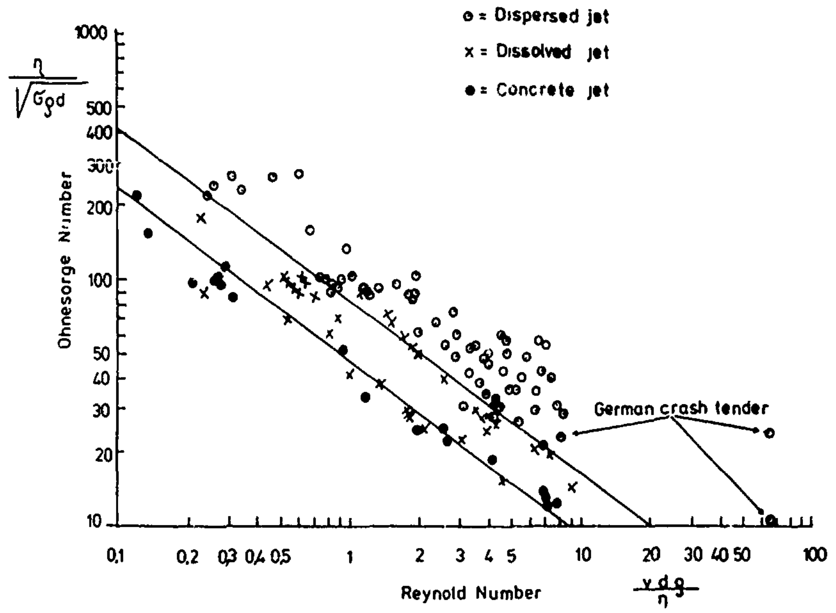

Fig. 29 Dependence of the configuration of a foam jet on the Ohnesorge- and Reynolds-Number

Compound	Efficacy	C.	E.	C.	E.
N_2	0.1	KNO_3	1.4	$(C_2H_5)_3PO_4$	5.1
SiO_2	0.2	KJ	1.6	$(CH_3)_3PO_4$	5.3
CO_2	0.2	$CuCl_2$	1.9	$K_2C_2O_4 \cdot H_2O$	5.8
SO_2	0.3	CH_3Br	1.9	PBr_3	6.0
HCl	0.4	HBr	1.9	$SbCl_3$	6.3
$SiHCl_3$	0.5	Na_2SiF_6	2.1	K_2CrO_4	6.3
NaCl	0.5	$KHCO_3$	2.3	Na_3AlF_6	6.6
NH_4Cl	0.5	$Na_2C_2O_4$	2.3	PbO	7.2
$CHCl_3$	0.7	K_2SO_4	2.3	$POCl_3$	7.3
$NaNO_3$	0.7	CH_2BrCl	2.4	$TiCl_4$	7.3
$SOCl_2$	0.8	$SiCl_4$	2.5	BBr_3	7.7
SF_6	0.8	CF_2BrCl	2.7	$K_2C_2O_4$	8.3
KCl	0.9	$AlCl_3$	2.8	K_3AlF_6	8.8
Na_2CO_3	0.9	$GeCl_4$	2.8	PCl_3	9.2
CCl_4	1.0	$SnCl_4$	2.8	$PSBr_3$	9.2
SO_2Cl_2	1.0	$Ba(NO_3)_2$	3.0	$PSCl_3$	10.6
$(C_2H_5)_2\ SO_4$	1.2	CF_3Br	3.2	$Na_2[Fe(CN)_5NO] \cdot 2H_2O$	15.5
KBr	1.2	K_2CO_3	3.2	$K_4Fe(CN)_6 \cdot 3H_2O$	16.4
$NaHCO_3$	1.2	$AsCl_3$	3.6	$K_4Fe(CN)_6$	46.3
S_2Cl_2	1.3	Na_2SO_3	3.9	CrO_2Cl_2	57.5
$Si(CH_3)_4$	1.3	CF_2Br_2	4.5	$Fe(CO)_5$	81.2
				$Pb(C_2H_5)_4$	98.6

Table 1 Extinguishing efficiency of chemical compounds

Foam forming agent	area	application rate $l/m^2 \cdot min$
Light Water	250	0,8
Fluoroprotein	150	1,33
Synthetic	75	2,66
Protein	50	4,0

Table 2 Maximum size of burning fuel area, which could be extinguished with a 200 l/min foam nozzle

SELECTIVE BIBLIOGRAPHY

This Bibliography with Abstracts has been prepared to support AGARD Lecture Series No. 123 by the Scientific and Technical Information Branch of the National Aeronautics and Space Administration, Washington, D.C., in consultation with the Lecture Series Director, Mr B H.Botteri.

UTTL: The F-16 Halon tank inerting system

AUTH: A/KLEIN, J. K. PAA: A/(USAF, Aeronautical Systems Div., Wright-Patterson AFB, OH) American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Conference, Dayton, OH, Aug. 11-13, 1981, 9 p.

ABS: The F-16 multimission fighter employs a new lightweight approach towards providing fuel tank inerting. The F-16 inerting system stores and effectively distributes Halon 1301 (bromotrifluoro-methane) to the air space above the fuel level to provide a nonexplosive atmosphere within the fuel tanks when activated. Background information includes a trades study with alternate inerting concepts. Resolution of component and system development problems is discussed and engine and airframe compatibility testing as well as system leve' tests are detailed. The results of initial F-16 operating experience is highlighted and a projection is made towards future applications. It is concluded that halon fuel tank inerting is a viable candidate for tactical and strategic aircraft weapon systems.

RPT#: AIAA PAPER 81-1638 81/08/00 81A43138

UTTL: Fireworthiness of transport aircraft interior systems

AUTH: A/PARKER, J. A.; B/KOURTIDES, D. A. PAA: B/(NASA, Ames Research Center, Moffett Field, CA) CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. American Institute of Aeronautics and Astronautics, Thermophysics Conference, 16th, Palo Alto, CA, June 23-25, 1981, 13 p.

ABS: This paper presents an overview of certain aspects of the evaluation of the fireworthiness of transport aircraft interiors. First, it addresses the key materials question concerning the effect of interior systems on the survival of passengers and crew in the case of an uncontrolled fire. Second, it examines some technical opportunities that are available today through the modification of aircraft interior subsystem components, modifications that may reasonably by expected to provide improvements in aircraft fire safety. Cost and risk benefits still remain to be determined.

RPT#: AIAA PAPER 81-1142 81/06/00 81A39131

UTTL: Past and future trends in structures and dynamics

AUTH: A/BADER, R. M.; B/GOESCH, W. H.; C/OLSEN, J. J. PAA: C/(USAF, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio) American Institute of Aeronautics and Astronautics, Annual Meeting and Technical Display on Frontiers of Achievement, Long Beach, Calif., May 12-14, 1981. 7 p.

ABS: An historical review and a series of prognostications based on current developments are presented for the fields of structural design and structural dynamics analysis. It is shown that while weight and cost reduction and improved durability have been the primary forces in structural technology development in the past, emphasis has shifted to such things as productivity, quality assurance, low observables for military aircraft and increased fuel efficiency. Prominent among recent advances in future developments are damage tolerance durability, computer-aided design, active flutter suppression, adhesive bonding of primary structures, cast aluminum structures, titanium and graphite-epoxy primary aircraft structures, aeroelastic tailoring composites, metal matrix composites, and radar-absorbing structures.

RPT#: AIAA PAPER 81-0896 81/05/00 81A32921

UTTL: General aviation accidents - Postcrash fires and how to prevent or control them Aircraft Engineering, vol. 53, Jan. 1981, p. 12-17.

ABS: Approximately 8.0% of the 22,002 general aviation accidents during the 1974-1978 period resulted in post-crash fires. Of these, about 59% resulted in fatalities, as compared to only 13.3% of accidents without fire. Three case histories (involving three different types of aircraft) illustrate accidents that would have been survivable had it not been for the post-crash fires. It is felt that fire safety would be enhanced by control of ignition sources and by fuel modification techniques. Fuel containment appears to be the most feasible technique for fire prevention. Existing regulations do not adequately provide minimum standards for improving the crash-fire survivability of newly certified aircraft. 81/01/00 81A24058

UTTL: Materials for fire resistant passenger seats in aircraft

AUTH: A/TESORO, G.; B/MOUSSA, A. PAA: B/(MIT, Cambridge, Mass.) CORP: Massachusetts Inst. of Tech., Cambridge. In: Fire retardants; Proceedings of the European Conference on Flammability and Fire Retardants, Copenhagen, Denmark, July 13, 14, 1978. (A80-48751 21-27) Westport, Conn., Technomic

Publishing Co., Inc., 1980, p. 159-173.
ABS: The paper considers the selection of cushioning foam and upholstery fabric materials for aircraft passenger seats. Polyurethane, polychloroprene, polyimide, and polyphosphazene are the foam materials considered; and a variety of commercial and developmental fabrics (including wool, cotton, synthetics, and blends) are examined. Viable approaches to the design of fire-resistant seat assemblies are indicated. Results of an experimental laboratory study of fabrics and fabric/foam assemblies exposed to external point-source radiative heat flux are discussed. 80/00/00 80A48757

UTTL: Emergency landings on a carpet of foam
AUTH: A/SCHEICHL, L. Airport Forum, vol. 10, Apr. 1980, p 35, 36, 39 (3 ff.).
ABS: Emergency landing by aircraft with faulty landing gear on carpets of foam laid out on a runway is studied. The theoretical and experimental fundamentals of foaming techniques are reviewed with attention given to the characteristics of the various types of foam. Foam equipment is discussed including runway foaming trailers and water trailers. 80/04/00 80A33292

UTTL: Post-crash fuel fire hazard measurements in a wide body aircraft cabin
AUTH: A/HILL, R. G.; B/SARKOS, C. P. PAA: B/(FAA, National Aviation Facilities Experimental Center, Atlantic City, N.J.) Journal of Fire and Flammability, vol. 11, Apr. 1980, p. 151-163.
ABS: This paper describes a full-scale wide-body test article for studying post-crash cabin fire hazards produced by an external fuel fire adjacent to a cabin door opening. Seventy two tests were conducted at various ambient wind conditions and fire sizes without interior materials. This work was the first phase of a study to realistically characterize post-crash cabin fire hazards. Data are presented and discussed pertaining to the effect of ambient wind on the rate of hazard accumulation inside the cabin, stratification of heat, smoke and toxic gases, the effect of fire size on thermal radiation through the opening, and the relative importance of heat, smoke and carbon monoxide in a fuel-dominant fire. 80/04/00 80A29025

UTTL: Flammability of cabin furnishing materials
AUTH: A/RAMSDEN, J. M. Flight International, vol. 116, Oct. 6, 1979, p. 1099-1101.
ABS: The results of flammability testing of cellular plastic cabin furnishings are surveyed. It is noted that many survivable accidents have been fatal, with death resulting from fire or smoke rather than from impact. It is reported that tests carried out by the United Kingdom Fire Research Station have found that the burning of polyurethane foam in bulk quickly generates very high temperatures and thick smoke, with flames at least 12 meters from the polyurethane. Temperatures of over 1,000 C and higher were reached melting the steel plated flooring of the test rig. Other hazards in addition to smoke and carbon monoxide are the production of hydrogen cyanide and other toxic gases. In addition, an American NTSB report, citing the use of kerosene type fuels as a factor in reduced fatalities due to fire and smoke, is covered. Finally, attention is given to future research such as the feasibility of non-flammable cabin attendant uniforms. 79/10/06 79A53722

UTTL: Bioassay of thermal protection afforded by candidate flight suit fabrics
AUTH: A/KNOX, F. S., III; B/WACHTEL, T. L.; C/MCCAHAN, G. R., JR. PAA: C/(U.S. Army, Aeromedical Research Laboratory, Fort Rucker, Ala.) Aviation, Space, and Environmental Medicine, vol. 50, Oct. 1979, p. 1023-1030.
ABS: Four thermally protective flight suit fabrics designed to protect the aviator from the thermal environment of a post-crash fire were tested by porcine bioassay to determine their mitigating effects on skin burning. A JP-4 fueled furnace with a mean heat flux of 3.07 cal/sq cm per sec was used as a heat source to study the protective properties of 4.8-oz. twill weave Nomex aramide, 4.5-oz. stabilized twill weave polybenzimidazole, 4.8-oz. plain weave experimental high-temperature polymer (HT4) and 4.8-oz. plain weave Nomex aramide on a porcine model of human skin. Results of statistical analyses of clinical and microscopic data indicate that all fabrics tested provide essentially the same degree of thermal protection, although HT4 is slightly better in attenuating heat flux. When used with a cotton T-shirt or an air gap, however, protection was improved for all fabrics and in all configurations. It is suggested that the improvement of flight suits can be achieved by the redesign of current uniforms and fabrics to include multiple layers. 79/10/00 79A52280

UTTL: Lockheed urges hydrogen fuel   Interavia, vol. 34, Sept. 1979, p. 872, 873.

ABS: The use of hydrogen as a future aircraft propellant is discussed and some advantages and disadvantages of using methane as another alternate source are examined. Although hydrogen is seen as a dangerous fuel source, its advantages clearly outweigh its disadvantages. First, it is noted that because hydrogen is lighter than air, a fire ignition would tend to roar upward and not expand sideways like a liquid fuel fire. Second, hydrogen burns cleanly and consistently, providing considerable benefits in the design of future power plants. Last, its exhaust consists mainly of water and therefore a hydrogen-fueled engine would create even less air pollution than the cleanest of modern petroleum-burning turbofans. The only disadvantage noted here is the apparent danger because of its high combustibility, and it is concluded that hydrogen may be the best alternative to many present-day energy problems.   79/09/00   79A49224

UTTL: Fuel on fire - Rapid response to a military problem

AUTH: A/BOYLE, D.   Interavia, vol. 34, June 1979, p. 554-556.

ABS: Equipment developed by Graviner England for extinguishing fuel fires in aircraft is analyzed, considering that such a system has to operate in milliseconds if suppression is to be effective. Two methods of detection are presented: (1) detection of the impact shock wave through the fuel tank, and (2) detection of flame radiation. The latter, by reacting only to a flame, eliminates the possibility of releasing extinguishant when no fire has occurred. The ultraviolet sensor which consists of a hydrogen and inert gas filled glass bulb containing two metal electrodes is discussed in detail. Its quick response time allows for several 'readings' per millisecond, thus reducing the chance of errant flashes or rays triggering the system. An explosive charge releases the potassium cryolite extinguishant from the cone shaped suppressor unit. The results of a demonstration for the U.S. Army are presented, noting various contract possibilities.   79/06/00   79A38090

UTTL: Crash-resistant fuel systems for general aviation aircraft

AUTH: A/EDWARDS, W. T.;   B/PERRELLA, W. M., JR.   PAA: A/(FAA, National Aviation Facilities Experimental Center, Atlantic City, N.J.);   B/(FAA, Seattle, Wash.)   Society of Automotive Engineers, Business Aircraft Meeting and Exposition, Wichita, Kan., Apr. 3-6, 1979. 13 p.

ABS: A significant percentage of general aviation aircraft accidents result in postcrash fires due to the ignition of spilled fuel. This condition often causes further injury or even death to the occupants. Testing was undertaken to examine the performance of light-weight, flexible, crash-resistant fuel cells with frangible fuel line couplings. Included in the experiments were four full-scale crash tests of a typical light twin-engined aircraft. In three of these tests, the crash-resistant fuel system performed satisfactorily. However, the fourth test, which used the lightest weight tanks, resulted in tank failures which indicated a possible lower strength limit to the tank material.

RPT#: SAE PAPER 790592   79/04/00   79A36726

UTTL: Crashworthiness analysis of field investigation of business aircraft accidents

AUTH: A/SNYDER, R. G.;   B/ARMSTRONG, T. J.   PAA: B/(Michigan, University, Ann Arbor, Mich.)   Society of Automotive Engineers, Business Aircraft Meeting and Exposition, Wichita, Kan., Apr. 3-6, 1979. 15 p. Research supported by the University of Michigan.

ABS: During the period 1964-1977 some 7,351 aircraft engaged in business flying, and 883 in corporate/executive operations, were involved in accidents reported by the NTSB. These accidents were reviewed utilizing the University of Michigan Computerized Accident Files to provide an overall view of the incidence and nature of business/executive aircraft accidents relative to occupant crash injuries. In addition more detailed case studies of selected accidents investigated including a Lear Jet 25B, Cessna 421, Beech Volpar Model 18, and Ted Smith Aerostar 601, are provided to illustrate specific types of crashworthiness, occupant protection, or post-crash emergency egress findings applicable to business/executive operations. Post-crash fire was reported in 29 cases (16.3%) during the 3-year period (1975-1977). Emergency egress problems involving smoke and fire are discussed. Data from 1975-1977 indicate that the chances of being fatally injured in an accident is significantly greater than receiving serious injury, suggesting a lack of crashworthy performance which may be predicted to improve as more accidents occur in which crew shoulder harnesses are installed and worn.

RPT#: SAE PAPER 790587   79/04/00   79A36721

UTTL: Lightning protection from aircraft
AUTH: A/JAEGER, D. PAA: A/(Messerschmitt-Boelkow-Blohm GmbH, Ottobrunn, West Germany) Deutsche Gesellschaft fuer Luft- und Raumfahrt and Hermann-Oberth-Gesellschaft, Deutscher Luft- und Raumfahrtkongress, Darmstadt, West Germany, Sept. 19-23, 1978, Paper. 35 p. In German.
ABS: Protection of metal aircraft, partly plastic aircraft, and helicopters from lightning is discussed with attention to the nature of lightning and its interaction with an aircraft. The relation between lightning parameters and lightning effects is considered. It is suggested that satisfactory procedures have been developed for protecting metal aircraft from lightning, but new aircraft, made partly from plastic and containing complicated avionics, will require the development of new systems for protection against lightning. 78/09/00 79A14105

UTTL: Antimisting fuel kinematics related to aircraft crash landings
AUTH: A/SAN MIGUEL, A. PAA: A/(U.S. Naval Weapons Center, China Lake, Calif.) Journal of Aircraft, vol. 15, Mar. 1978, p. 137-142. U.S. Department of Transportation
ABS: An approximate analysis is presented to quantitize the kinematic behavior of antimisting Jet A fuel in an airstream representative of survivable aircraft crash landings. Antimisting fuel data were generated from a fuel-expulsive airfoil placed in an airstream adjacent to a pulsing propane flame. Measurements of burning-front velocities and accelerations were obtained from a camera located within the airfoil. These data were used in the analysis to predict the diameter, shear stress, and shearing strain rate of the average particle of antimisting fuel in the airstream under the airfoil. A description is given of the airflow-airfoil apparatus in the context of its simulation of crash landing conditions. The feasibility of using antimisting agents to suppress a fuel fire during a crash landing is evaluated. 78/03/00 78A28147

UTTL: Extinguishants for aircraft fire fighting foaming agents - Protein, fluoroprotein and AFFF
AUTH: A/DIMAIO, L. R. PAA: A/(National Foam System, Inc., Lionville, Pa.) National Fire Protection Association, International Seminar on Aircraft Rescue and Fire Fighting, Geneva, Switzerland, Sept. 13-17, 1976, Paper. 12 p.
ABS: The three foams which are used as primary agents include a regular type involving protein, an aqueous film-forming foam, and a fluoroprotein type. The regular protein-type mechanical foams, based on hydrolyzed protein, are and have been in use for over 30 years. The AFFF or aqueous film-forming foam makes use of fluorinated surfactants. The fluoroprotein type is a protein-based liquid which is modified by the addition of a selected fluorinated surfactant which bonds itself loosely to the protein to give the foam oleophobicity. 76/09/00 77A40946

UTTL: Cabin materials, their combustion properties and the nature of noxious and toxic gases in fires - The assessment of the human survival response during aircraft accidents
AUTH: A/EINHORN, I. N. PAA: A/(Utah, University, Salt Lake City, Utah) National Fire Protection Association, International Seminar on Aircraft Rescue and Fire Fighting, Geneva, Switzerland, Sept. 13-17, 1976, Paper. 24 p. Navy-supported research
ABS: Analysis of the factors involved in numerous aircraft fires, where impact injuries were not implicated, reveals that most deaths are not due to flame contact, but are a consequence of the production of carbon monoxide, nitrogen oxides, and other combustion products, such as aldehydes, ketones, low-molecular-weight alcohols, hydrogen cyanide, and other toxic species. This paper deals with behavioral and bioassay protocol developed to assess the effect of combustion products on human survival during fire exposure. The major techniques many toxicologists use to assess the toxicological parameters encountered during 'real fires' are reviewed. Finally, a full-scale adaptation of laboratory procedures developed for use in actual aircraft fire scenarios is described. 76/09/00 77A40945

UTTL: Fire injuries and the pathology and neuropathology of single acute exposures to combustion products - Pathology and neuropathology of aircraft fire victims
AUTH: A/GRUNNET, M. L. PAA: A/(Utah, University, Salt Lake City, Utah) National Fire Protection Association, International Seminar on Aircraft Rescue and Fire Fighting, Geneva, Switzerland, Sept. 13-17, 1976, Paper. 17 p.
ABS: A review is presented of the factors leading to human incapacitation or death in aircraft accidents involving fire. Special emphasis has been directed toward the toxicological effects produced during the thermal decomposition and combustion of natural and synthetic materials. The results of controlled small-scale laboratory combustion inhalation

experiments are presented. The specific effects of particular toxicants and mixtures of toxicants on tissue and organ systems are discussed. The importance of the utilization of both an analytical bioassay protocol and behavioral procedure in the evaluation of untoward human physiological response during fire exposure is discussed in detail. 76/09/00 77A40942

UTTL: A composite system approach to aircraft cabin fire safety

AUTH: A/KOURTIDES, D. A.; B/PARKER, J. A.; C/GILWEE, W. J., JR.; D/LERNER, N. R.; E/HILADO, C. J.; F/LABOSSIERE, L. A.; G/HSU, M.-T. PAA: D/(NASA, Ames Research Center, Moffett Field, Calif.); F/(San Francisco, University, San Francisco, Calif.); G/(San Jose State University, San Jose, Calif.) CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif.; San Francisco Univ., Calif.; San Jose State Univ., Calif. National Fire Protection Association, International Seminar on Aircraft Rescue and Fire Fighting, Geneva, Switzerland, Sept. 13-17, 1976, Paper. 49 p.

ABS: The thermochemical and flammability characteristics of two polymeric composites currently in use and seven others being considered for use as aircraft interior panels are described. The properties studied included (1) limiting oxygen index of the composite constituents; (2) fire containment capability of the composite; (3) smoke evolution from the composite; (4) thermogravimetric analysis; (5) composition of the volatile products of thermal degradation; and (6) relative toxicity of the volatile products of pyrolysis. The performance of high-temperature laminating resins such as bismaleimides is compared with the performance of phenolics and epoxies. The relationship of increased fire safety with the use of polymers with high anaerobic char yield is shown. Processing parameters of one of the bismaleimide composites is detailed. 76/09/00 77A40937

UTTL: Combined agent techniques and new agent developments

AUTH: A/MUTZELBURG, W. PAA: A/(Flughafen Berlin-Tegel, Berlin, West Germany) National Fire Protection Association, International Seminar on Aircraft Rescue and Fire Fighting, Geneva, Switzerland, Sept. 13-17, 1976, Paper. 28 p. In German.

ABS: The use of suitable materials for the production of foam in aircraft fire-fighting applications is discussed, taking into account the definitions of terms employed in the description of the characteristics and the effectiveness of the extinguishing agent. Details concerning the application of the various available agents are discussed and the effects produced by the different agents are compared. A description is also presented of a new extinguishing agent which utilizes the heat of the fire for the foam-generating process. The agent consists essentially of a AFFF-Halon emulsion. 76/09/00 77A40933

UTTL: Vehicles and extinguishants

AUTH: A/PIZEL, R. PAA: A/(Aeroport de Paris, Service Etudes Securite, Orly Airport, France) National Fire Protection Association, International Seminar on Aircraft Rescue and Fire Fighting, Geneva, Switzerland, Sept. 13-17, 1976, Paper. 9 p. In French.

ABS: Three fire-extinguishing foams used to combat aircraft fires are compared with respect to the quantities of precursor water and powder required for different categories of airports. The three foams are a protein foam, an aqueous film-forming foam, and a fluoroprotein foam (FP 70). The properties of the fluoroprotein powder are examined. Characteristics of the fire-fighting vehicles which transport the foam precursors are discussed, and powder and water delivery rates are examined. Other topics, such as fire-fighting in a fog and the development of foam-delivering boats for use at airports adjacent to a body of water, are considered. 76/09/00 77A40932

UTTL: Criteria for large scale fire testing of aircraft interiors

AUTH: A/WILLIAMSON, R. B.; B/HASEGAWA, H. PAA: B/(California, University, Berkeley, Calif.) National Fire Protection Association, International Seminar on Aircraft Rescue and Fire Fighting, Geneva, Switzerland, Sept. 13-17, 1976, Paper. 32 p.

ABS: Key considerations in designing aircraft fire safety include: controlling the risk of fire outbreak; containing fire within interior spaces; maintaining structural integrity and air-worthiness during fires; and reducing the toxic threat of combustion products. A test is developed for the containment of fire in interior spaces, similar to the standard fire containment test for building materials. The test allows comparative data to be obtained on the fire resistance of newly-developed aircraft interior panels. Toxic gas analyses and bioresponse data are also given, and calculations are made to determine the amount of time needed to burn through the test specimen, to reach excessive temperature levels on the back face of panels, and to reach untenable smoke conditions. 76/09/00 77A40924

UTTL: Cabin safety by crash survival
AUTH: A/NELSON, R. W. PAA: A/(FAA, Washington, D.C.) Society of Automotive Engineers, Business Aircraft Meeting, Wichita, Kan., Mar. 29-Apr. 1, 1977, 15 p.
ABS: This paper briefly traces development of crashworthiness requirements promulgated in pertinent airworthiness standards for general aviation aircraft Primary emphasis is focused on protection of aircraft occupants in the survivable crash environment. The evolution of government involvement in civil aviation and the FAA role in aviation safety are discussed, as well as the regulatory rulemaking process. A review of past and present crash protection requirements is presented. Pending regulatory action and future goals are mentioned.
RPT#: SAE PAPER 770485 77/03/00 77A37099

UTTL: Pro-static agents in jet fuels
AUTH: A/LEONARD, J. T. PAA: A/(U.S. Navy, Naval Research Laboratory, Washington, D.C.) In: International Congress on Electrostatics, 3rd, Grenoble, France, April 20-22, 1977, Proceedings. (A77-37008 16-01) Paris, Societe de Chimie Industrielle, 1977, p. 18-a to 18-e.
ABS: It has been hypothesized that many fires and explosions during the fueling of aircraft occur because the fuel is unusually electrostatically active as a result of contamination by trace amounts of pro-static agents. A study was conducted to determine if, by screening a wide variety of polar and ionic compounds and fuel additives, it would be possible to identify the types of compounds that are responsible for unusually high electrostatic activity in hydrocarbon fuels. Thirty-nine compounds and 24 fuel additives were screened for possible pro-static activity by measuring the effects of these materials on the electroconductivity and the charging tendency of silica gel-treated n-heptane. 77/00/00 77A37010

UTTL: Fire testing of aircraft cabins
AUTH: A/DUSKIN, F. E. PAA: A/(Douglas Aircraft Co., Long Beach, Calif.) Journal of Fire and Flammability, vol. 8, Apr. 1977, p. 193-201.
ABS: A major aircraft corporation is currently engaged in aircraft fire-safety research and development programs. This effort includes full-scale fire testing of configurations representing commercial aircraft interiors. These tests are being conducted in a Cabin Fire Simulator (CFS), a double-walled steel cylinder 12 feet in diameter and 40 feet long equipped with a ventilation system, exhaust scrubber, and a nitrogen extinguisher system. An on-site computer is used to record thermal and gas-analysis data. Many series of tests have been conducted, one of which culminated in a full cabin lavatory fire test. Subsequent testing of lavatory modules has demonstrated the fire resistance of contemporary materials and the effectiveness of design improvements. 77/04/00 77A34489

UTTL: Survivability of the Army/Sikorsky YUH-60A helicopter
AUTH: A/FOULK, J. B. PAA: A/(United Technologies Corp., Sikorsky Aircraft Div., Stratford, Conn.) In: American Helicopter Society, Annual National Forum, 32nd, Washington, D.C., May 10-12, 1976, Proceedings. (A77-26851 11-01) Washington, D.C., American Helicopter Society, 1976, p. 1011-1 to 1011-21.
ABS: Design of the UTTAS YUH-60A combat helicopter to minimize detectability and vulnerability and maximize survivability and crashworthiness is discussed. Vulnerability of the rotor assemblies, tail rotor, fuel system, lubrication system, transmission system, and propulsion system to various levels of hostile threats and damage are described. Post-crash fire hazard, seating and retention of crew, emergency evacuation and delethalization of the YUH-60A interior, airframe survivability, and behavior in hard landing and emergencies are described. Reduction and masking of the acoustic signature (with elimination of impulse rotor noise), visual signature (and nap-of-earth flying capability), IR signature, and radar signature, and countermeasures for these signatures, are dealt with. 76/00/00 77A26857

UTTL: Oxygen-induced aircraft cabin fire
AUTH: A/BRENNEMAN, J. J. CORP: United Air Lines, Inc., Chicago, Ill. 71/00/00 79N73673

UTTL: Aviation fuel safety, 1975 CORP: Coordinating Research Council, Inc., New York. CSS: (Aviation Fuel, Lubricant and Equipment Research Committee.)
RPT#: CRC-482 75/11/00 78N74307

UTTL: Aircraft fire fighters protective proximity clothing
AUTH: A/TYLER, M. C.; B/DEISER, E. E. CORP: DOD Aircraft Ground Fire Suppression and Rescue Office, Wright-Patterson AFB, Ohio.
RPT#: AD-A025935 DOD-AGFSRS-76-6 75/08/00 77N71713

UTTL: Investigation of the structural degradation and personnel hazards resulting from helicopter composite structures exposed to fires and/or explosions
AUTH: A/SCHILTZ, R. J., JR. CORP: Textron Bell Helicopter Fort Worth, Tex.
ABS: A program was undertaken to investigate the structural degradation and personnel hazards resulting from exposure of helicopter composite structures to fire and/or explosion. The program consisted of a technical survey, a test program, and an analysis phase. A major part of the technical survey was a literature survey. In addition, organizations working in the fields of interest were contacted for information, and some were visited for further, detailed discussions. The computer programs currently available for modeling enclosure fires were screened, and one was chosen for further study. The test program consisted of a series of tests on two representative helicopter structures: a sheet-stiffened, built-up door of Kevlar 49 fabric impregnated with an epoxy resin, and a honeycomb sandwich fuselage shell structure of graphite/epoxy fabric skins on a Nomex honeycomb core. The tests conducted on materials from these structures were smoke generation tests, and structural degradation tests. Ballistic tests on the complete test article were conducted to determine whether the structures would ignite under HEI impact conditions. Based on the survey and testing, design criteria for structural composite components were investigated and, when appropriate, formulated.
RPT#: AD-A104757 USAAVRADCOM-TR-81-D-16 81/03/00 82N12057

UTTL: The toxicity of gases from the thermal decomposition of combustible materials. A test chamber prototype
AUTH: A/PICART, P. E.; B/DELCROIX, J. P.; C/GUERBET, M. CORP: Laboratoire Central de Biologie Aerospatiale, Paris (France). CSS: (Div. de Chimie-Toxicologie.) In AGARD Toxic Hazards in Aviation 10 p (SEE N81-27791 18-52)
ABS: When fire breaks out in a closed environment, as in an aircraft cabin, evacuation is not immediately possible and thus it is necessary to establish minimum survivable conditions. In this case, toxic gases become a major problem. That is why it is necessary to select materials that present a minimum of toxicity in case of an onboard fire. A test chamber was developed that permits the examination of physical parameters involved with the thermal degradation of aircraft materials, with emphasis on the toxicity of combustion gases. The test chamber is described and the results of tests run on three materials (wood, polyurethane resins, polyvinyl chloride) are presented. 81/04/00 81N27799

UTTL: Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, volume 2A
AUTH: A/ENDERS, J. H.; B/WOOD, E. C. CORP: Federal Aviation Administration, Washington, D.C. CSS: (Office of Aviation Safety.)
ABS: The Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee and its technical supporting groups spent nearly 13 months from May 1979 through June 1980 examining the factors affecting the ability of the aircraft cabin occupant to survive in the post-crash fire environment and the range of solutions available. Presentations were made to the SAFER Committee by Committee members, technical supporting groups, the FAA, citizens and private firms. The broadly-constituted body of information developed and presented to the Committee formed the basis for Committee Findings and Recommendations. This volume contains technical subcommittee submittal related to interior cabin material's flammability, short term, solutions to the fire hazard and recommendations on Post Crash Fire Reduction.
RPT#: AD-A099147 FAA-ASF-80-4-VOL-2A 80/06/26 81N27065

UTTL. Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, volume 2B
AUTH: A/ENDERS, J. H.; B/WOOD, E. C. CORP: Federal Aviation Administration, Washington, D.C. CSS: (Office of Aviation Safety.)
ABS: The factors affecting the ability of the aircraft cabin occupant to survive in the post crash fire environment and the range of solutions available are presented. The proceedings of the SAFER Committee and the FAA's responses to the committee's recommendations are reported. Information on crew protection and passenger evacuation is given.
RPT#: AD-A099176 FAA-ASF-80-4-VOL-2B 80/06/26 81N27064

UTTL: Testing of aircraft passenger seat cushion materials. Full scale, test description and results, volume 1
AUTH: A/SCHUTTER, K. J.; B/GAUME, J. G.; C/DUSKIN, F. E. CORP: Douglas Aircraft Co., Inc., Long Beach, Calif.
ABS: Eight different seat cushion configurations were subjected to full-scale burn tests. Each cushion configuration was tested twice for a total of sixteen tests. Two different fire sources were used. They consisted of one liter of Jet A fuel for eight tests and a radiant energy source with propane flame for eight tests. Both fire sources were ignited by a propane flame. During each test, data were recorded for smoke density, cushion temperatures, radiant heat flux, animal response to combustion products, rate of weight loss of test specimens, cabin temperature, and for the type and content of gas within the cabin atmosphere. When compared to existing passenger aircraft seat cushions, the test specimens incorporating a fire barrier and those fabricated from advanced materials, using improved construction methods, exhibited significantly greater fire resistance.
RPT#: NASA-CR-160995-VOL-1 81/02/00 81N25051

UTTL: Testing of aircraft passenger seat cushion material, full scale. Data, volume 2
AUTH: A/SCHUTTER, K. J.; B/GAUME, J. G.; C/DUSKIN, F. E. CORP: Douglas Aircraft Co., Inc., Long Beach, Calif.
ABS: Burn characteristics of presently used and proposed seat cushion materials and types of constructions were determined. Eight different seat cushion configurations were subjected to full scale burn tests. Each cushion configuration was tested twice for a total of 16 tests. Two different fire sources were used: Jet A-fuel for eight tests, and a radiant energy source with propane flame for eight tests. Data were recorded for smoke density, cushion temperatures, radiant heat flux, animal response to combustion products, rate of weight loss of test specimens, cabin temperature, and type and content of gas within the cabin. When compared to existing seat cushions, the test specimens incorporating a fire barrier and those fabricated from advanced materials, using improved construction methods, exhibited significantly greater fire resistance. Flamability comparison tests were conducted upon one fire blocking configuration and one polyimide configuration.
RPT#: NASA-CR-160963 MDC-J4673-VOL-2 80/11/00 81N25050

UTTL: Effect of thermal radiation on the integrity pressurized aircraft evacuation slides and slide materials
AUTH: A/BROWN, L. J., JR.; B/NICHOLAS, E. B. CORP: Federal Aviation Administration, Atlantic City, N.J. CSS: (Technical Center.)
ABS: Seventeen full-scale fire tests were conducted to examine the effect of thermal radiation from a large fuel fire on the integrity of pressurized aircraft evacuation slides. Urethane nylon, aluminized urethane nylon, neoprene nylon, aluminized neoprene nylon, and aluminized neoprene Kevlar slides were tested at various distances from a 30- by 30-foot fire pit. Heat flux at the slide, inflation pressure, and air temperature were measured and motion pictures and photographs were taken during these full-scale tests. At an average heat flux level of 1.5 Btu/sq ft-second (sec) (15 feet from edge of fire pit) inservice evacuation slides failed in a nonseam area in 23 to 32 seconds. With an aluminized coating applied to the airholding surfaces, the time failure increased by more than a factor of two at the same test condition. A laboratory test method, suitable for materials qualification, was developed that exposes an evacuation slide material to a preselected radiant heat flux and pressure. Tests were conducted on new materials submitted by slide and material manufacturers, and material samples taken from the undamaged areas of full-scale test slides. A good correlation was demonstrated between the failure times measured in full-scale and laboratory tests.
RPT#: AD-A098179 FAA-CT-81-28 81/03/00 81N24039

UTTL: Study of materials performance model for aircraft interiors
AUTH: A/LEARY, K.; B/SKRATT, J. CORP: ECON, Inc., San Jose, Calif.
ABS: A demonstration version of an aircraft interior materials computer data library was developed and contains information on selected materials applicable to aircraft seats and wall panels, including materials for the following: panel face sheets, bond plies, honeycomb, foam, decorative film systems, seat cushions, adhesives, cushion reinforcements, fire blocking layers, slipcovers, decorative fabrics and thermoplastic parts. The information obtained for each material pertains to the material's performance in a fire scenario, selected material properties and several measures of processability.
RPT#: NASA-CR-152378 80/08/31 81N20063

UTTL: Fireworthiness of transport aircraft interior systems
AUTH: A/PARKER, J. A.; B/KOURTIDES, D. A. CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. In NASA. Langley Research Center The 1980 Aircraft Safety and Operating Probl., Pt. 2 p 453-479 (SEE N81-19056 10-03)
ABS: The key materials question is addressed concerning the effect of interior systems on the survival of passengers and crew in the case of an uncontrolled transport aircraft fire. Technical opportunities are examined which are available through the modification of aircraft interior subsystem components. modifications that may reasonably be expected to provide improvements in aircraft fire safety. Subsystem components discussed are interior panels, seats, and windows. By virtue of their role in real fire situations and as indicated by the results of large scale simulation tests, these components appear to offer the most immediate and highest payoff possible by modifying interior materials of existing aircraft. These modifications have the potential of reducing the rate of fire growth, with a consequent reduction of heat, toxic gas, and smoke emission throughout the habitable interior of an aircraft, whatever the initial source of the fire. 81/03/00 81N19061

UTTL: Summary of aviation safety program resumes. Cabin safety
AUTH: A/HARRISON, J. H. CORP: Federal Aviation Administration, Washington, D.C. CSS: (Office of Aviation Safety.)
ABS: This report contains a Program Activity Resume and a Project Details listing of those activities supporting the FAA Cabin Safety Program. The Cabin Safety Activity Resume identifies three sub-programs relating to Inflight, Crashworthiness and Post Crash safety activities. The sub-programs are identified and reported in the Project Details listing which includes: Inflight Fire, Operational Hazards, Training Duties, Crash Scenario Definition, Structural Load Analysis, Crashworthy Fuel Tanks, Fuel Fire Hazard, Cabin Interior Materials, Crew Considerations, Crash Rescue, SAFER Advisory Committee and Evacuation Systems.
RPT#: AD-A091938 FAA-ASF-80-3 80/10/00 81N16027

UTTL: Special Aviation Fire and Explosion Reduction (SAFER) advisory committee, volume 1
AUTH: A/ENDERS, J. H.; B/WOOD, E. C. CORP: Federal Aviation Administration, Washington, D.C. CSS: (Office of Aviation Safety.)
ABS: The Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee and its technical supporting groups spent nearly 13 months from May 1979 through June 1980 examining the factors affecting the ability of the aircraft cabin occupant to survive in the post-crash fire environment and the range of solutions available. Having only a limited amount of time available, the Committee confined its examination to large transport category aircraft reasoning that recommendations developed could provide the necessary guidance for the FAA to address the broader spectrum of airplane and rotorcraft fire safety improvement. During the course of this assignment, certain topics that were outside the scope of the Committee, yet have some bearing on aircraft fire in general, were identified but not discussed by the Committee. Some of these topics were felt to be worthy of further examination by the FAA or by some other body of advisors constituted for that purpose. These topics are not addressed in this report. Presentations were made to the SAFER Committee by Committee members, technical supporting groups, the FAA, citizens and private firms. The broadly-constituted body of information developed and presented to the Committee formed the basis for Committee Findings and Recommendations. The Committee focused its recommendations on solutions or interim improvements.
RPT#: AD-A092016 FAA-ASF-80-4-VOL-1 80/06/26 81N15024

UTTL: Testimony of a panel consisting of: Lloyd E. Frisbee, Vice President, Engineering and Operations, Lockheed California Company, Lyle A. Wright, Director, Powerplant Engineering, Douglas Aircraft Company, accompanied by Doctor H. C. Schjelderup, Chief Technology Engineer, Materials and Process Engineering, and F. E. Duskin, Senior Design Engineer, Interiors Engineering, Douglas Aircraft Company
CORP: Committee on Public Works and Transportation (U. S. House). In its Aviation and Safety: Interior Compartment Mater. p 298-370 (SEE N81-13933 05-03)
ABS: Lockheed has conducted programs to improve aircraft material flame resistance and develop advanced techniques for firesafety testing in coordinated programs with other airframe companies, materials suppliers, and NASA. During this time, Lockheed has had active, continuous liaison with governmental agencies to develop firesafety testing techniques, study the feasibility and trade offs for advanced

aircraft fire management systems, and seek meaningful and productive areas of research and development in aircraft fire safety. Active support and participation was also maintained in technical committee work such as ASTM-F7 Committee on Aerospace Test Methods to standardize on flammability, smoke, and other combustion byproducts test techniques and to perform inter-laboratory comparison testing of flammability and smoke emission methods. Improved flammability and smoke test techniques have contributed to substantial improvements in flame resistance of aircraft interior construction material in all categories and an order of magnitude reduction in smoke emission of materials In other words, the smoke emission was reduced by an order of 10 times in the last few years. 79/00/00 81N13937

UTTL: Testimony of Richard W. Taylor, Vice President and Special Assistant to the President, and Eugene A. Bara, Chief Engineer, Payloads Systems, Boeing Commercial Airplane Company CORP: Committee on Public Works and Transportation (U. S. House). In its Aviation Safety: Interior Compartment Mater. p 159-297 (SEE N81-13933 05-03)

ABS: A brief review of the Boeing aircraft interior materials and fire test methods development programs is given. This activity has gone on for many years and contributed to the AIA crashworthiness program in 1968. As a result of these activities, the 747 was designed and built using the latest available technology, thereby establishing the requirements for wide body jet transports. Boeing's program in interior materials has continued and the highlights of the last five years are reviewed. 79/00/00 81N13936

UTTL: Testimony of James J. Kramer, Associate Administrator for Aeronautics and Space Technology, National Aeronautics and Space Administration, accompanied by John H. Enders, Project Manager, Aviation Safety Technology Office, John A. Parker, Chemical Research Projects Office, NASA-Ames Research Center, and Demitrius A. Kourtides, Chemical Research Projects Office, NASA-AMES Research Center CORP: Committee on Public Works and Transportation (U. S. House). In its Aviation Safety: Interior Compartment Mater. p 65-158 (SEE N81-13933 05-03)

ABS: The materials system development program FIREMEN (Fire Resistant Materials Engineering) is described. The program is carried out through contracts with the major aircraft manufacturers whereby they are funded to test and evaluate these advanced material systems under the real constraints of state of the art manufacturing processes, production schedules, costs, weight, and so forth. 79/00/00 81N13935

UTTL: Aviation safety: Interior compartment materials CORP: Committee on Public Works and Transportation (U. S. House). GPO Hearings before the Subcomm. on Oversight and Rev. of the Comm. on Public Works and Transportation, 96th Congr., 1st Sess., 25-26 Apr. 1979

RPT#: GPO-50-388 79/00/00 81N13933

UTTL: Engineering and development program plan aircraft crashworthiness

AUTH: A/CAIAFA, C. A.; B/NERI, L. M. CORP: Federal Aviation Administration, Atlantic City, N.J. CSS: (Technical Center.)

ABS: The Aircraft Crashworthiness Program Plan is designed to reduce or prevent aircraft occupants from incurring serious or fatal injuries in a survivable crash impact accident by incorporating crashworthy design features into the initial stages of fixed-wing and rotary-wing aircraft development. It describes a 5 year development program for both airplanes and rotorcraft. It identifies five major subprogram areas for study and analysis to accomplish the programs goals: (1) Airframes; (2) Cabin safety; (3) Fuel system protection; (4) Emergency evacuation system; and (5) Standards, criteria, and procedures. The plan emphasizes use of available background data, development of analytical techniques, validation of analytical techniques, validation of data to determine feasibility/acceptability and transmittal of appropriate data for consideration as the basis for regulation, standards, etc. The federal aviation administration groups, other Government agencies/departments and industry organizations participating in this effort are identified. Program schedule with milestones is presented. Program management and funding requirements are also identified.

RPT#: AD-A089431 FAA-CT-80 166 FAA-ED-18-6 80/06/00 81N10022

UTTL: Design concept for fuel fire facility scale-down

AUTH: A/PIERGALLINI, J. R. CORP: Naval Air Development Center, Warminster, Pa. CSS: (Aircraft and Crew Systems Technology Directorate.)

ABS: An all-weather, self-sustaining, indoor fuel-fire facility for the generation of data for the evaluation of burn-protective capacity of personal gear for naval aircrewmen and flight deck personnel in full-scale fuel fire exposures was developed. A scaled-down indoor version of the existing fuel-fire facility provided realistic data for protective-capacity analysis. An automated enclosed facility allows experiments to be conducted efficiently indoors in a closely controlled environment with minimal risk to personnel and surrounding and with more timely and consistent results in the analysis of data for burn protection of naval aircrewmen.

RPT#: AD-A084624 NADC-79227-60 , 79/08/00 80N32406

UTTL: General aviation accidents: Postcrash fires and how to prevent or control them CORP: National Transportation Safety Board, Washington, D. C. CSS: (Bureau of Technology.)

ABS: It was shown that postcrash fires occurred in approximately 8.0 percent of the 22,002 general aviation accidents during 1974-1978. About 59 percent of the accidents involving postcrash fire resulted in fatalities, while fatalities were involved in only 13.3 percent of those accidents without fire. It was demonstrated that feasible techniques for the containment of fuel exist. It was shown that fuel containment dramatically reduces fire injuries and deaths. It was shown that there are few regulations dealing with the postcrach fire problem in general aviation aircraft. Six recommendations to the Federal Aviation Administration for corrective action are given.

RPT#: NTSB-AAS-80-2 80/08/28 80N32354

UTTL: Antimisting kerosene

AUTH: A/SCHMIDT, H. W. CORP: National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. In its Aircraft Res. and Technol. for Future Fuels Jul. 1980 p 125-130 (SEE N80-29300 20-07)

ABS: The antimisting additive ((FM-9) was tested in terms of its propulsion systems performance. The effect of the additive on engine operation was evaluated, operating problems were identified, the adaptability of engines to antimisting kerosene was assessed, and the potential viability of this fuel for use in present and future fan jet engines was determined. 80/07/00 80N29319

UTTL: Advanced concept in aircraft crash firefighting using carbon tetrafluoride

AUTH: A/GEYER, G. B.: B/NERI, L. M.: C/URBAN, C. H. CORP: National Aviation Facilities Experimental Center, Atlantic City, N. J.

ABS: The feasibility of replacing a potentially lethal aircraft cabin environment with a cool habitable atmosphere which is nonsupportive of combustion during passenger evacuation in fire emergencies was investigated. Carbon tetrafluoride (CF4) was chosen as the fire extinguishant because of its very low toxicity and high molecular stability under thermal insult. Four large-scale experiments were performed in a completely instrumented cabin of a DC7 aircraft employing both Class A and B combustable materials. Three experiments were performed using the habitable inert atmosphere (27 volume percent CF4) discharging at the rate of 3,300 cubic feet per minute into the aircraft cabin through a window exit. For comparative purposes, the fourth experiment was performed using neat CF4 discharged from two simulated points of fuselage penetration by a ballistically-powered aircraft skin penetrator nozzle. The CF4-air atmosphere was capable of extinguishing nonsurvivable Class A and B cabin fires within 125 seconds or less during which time the cabin temperature was rapidly reduced and visual acuity slowly improved by smoke dilution during the Class A fire tests. Fire extinguishment by means of neat CF4 at the same discharge rate required approximately twice as long, and visibility within the cabin did not improve during the duration of the experiment.

RPT#: AD-A082936 FAA-NA-79-43 ESL-TR-79-40 80/03/00 80N24281

UTTL: Postcrash fuel fire hazard measurements in a wide-body aircraft cabin

AUTH: A/HILL, R. G.; B/JOHNSON, G. R.: C/SARKOS, C. P. CORP: National Aviation Facilities Experimental Center, Atlantic City, N. J. Original contains color illustrations

ABS: Results obtained utilizing a full-scale, wide-body test article for studying postcrash cabin hazards produced by an external fuel fire adjacent to a cabin door opening are described. Seventy-two tests were conducted at various ambient wind conditions and fire sizes in a fire-hardened cabin devoid of interior materials. Temporal data, taken at a large number of cabin locations, are presented and discussed pertaining to the effect of ambient wind on the rate of hazard accumulation inside of the cabin; stratification of heat, smoke, and toxic gases; the effect of fire size of thermal radiation through the opening; and the relative importance of heat, smoke, and carbon monoxide in a fuel-dominant fire. It is concluded that major stratification of hazards occurs in the cabin when the hazards are created by an external fuel fire, and that ambient wind determines the amount of hazards entering a cabin due to a given fuel fire.

RPT#: AD-A079548 FAA-NA-79-42 79/12/00 80N24280

UTTL: NASA technical advances in aircraft occupant safety

AUTH: A/ENDERS, J. H. CORP: National Aeronautics and Space Administration, Washington, D. C. Presented at the SAE Congr. and Exposition, Detroit, 27 Feb. - 3 Mar. 1978

ABS: NASA's aviation safety technology program examines specific safety problems associated with atmospheric hazards, crash-fire survival, control of aircraft on runways, human factors, terminal area operations hazards, and accident factors simulation. While aircraft occupants are ultimately affected by any of these hazards, their well-being is immediately impacted by three specific events: unexpected turbulence encounters, fire and its effects, and crash impact. NASA research in the application of laser technology to the problem of clear air turbulence detection, the development of fire resistant materials for aircraft construction, and to the improvement of seats and restraint systems to reduce crash injuries are reviewed.

RPT#: NASA-TM-80851 ISSN-0148-7191 78/00/00 80N15060

UTTL: Airflow effects on fires, part 2

AUTH: A/WEEMS, T.; B/GEBHARD, C. C.; C/CAMBURN, G. L. CORP: Air Force Flight Dynamics Lab., Wright-Patterson AFB, Ohio.

ABS: This report expands the knowledge of airflow effects on fuel fires initiated by nonnuclear combat damage obtained from previous work reported in JTCG/AS-T-75-001. An investigation is made into the influence of selected airflow parameters (coefficient of pressure and the boundary layer thickness) upon the blowout velocity for a variety of damage conditions and angles-of-attack.

RPT#: AD-A073486 JTCG/AS-76-T-006 79/05/00 80N13196

UTTL: Cabin hazards from a large external fuel fire adjacent to an aircraft fuselage

AUTH: A/BROWN, L. J., JR. CORP: National Aviation Facilities Experimental Center, Atlantic City, N. J.

ABS: Fourteen fire tests were conducted with a surplus, fire hardened DC 7 fuselage. The flame penetration and resulting accumulation of heat and smoke inside an aircraft cabin, produced by a large external fuel fire adjacent to a fuselage door opening, was measured and studied. Temperatures, light transmittances, and heat fluxes were measured. The effect of wind direction and velocity on the flame propagation and penetration were investigated.

RPT#: AD-A073494 FAA-NA-79-27 79/08/00 80N11050

UTTL: A review of Boeing interior materials and fire test methods development programs

AUTH: A/BARA, E. CORP: Boeing Commercial Airplane Co., Seattle, Wash In NASA Ames Res. Center Conf. on Fire Resistant Mater. p 167-181 (SEE N79-31166 22-03)

ABS: Total materials systems requirements, and government and industry programs are outlined along with a new fire test methodology, and the potential decrease in post crash fire hazards. The flammability, smoke and toxicity goals, and the scope of materials systems are tabulated. 79/07/00 79N31177

UTTL: Fuselage ventilation under wind conditions

AUTH: A/STUART, J. W. CORP: Jet Propulsion Lab., California Inst. of Tech., Pasadena. In NASA. Ames Res. Center Conf. on Fire Resistant Mater. p 127-134 (SEE N79-31166 22-03)

ABS: To determine realistic fuselage ventilation rates for post-crash fires and full-scale fire tests, the effects on wind-about fuselage ventilation rate of various parameters were studied. The parameters investigated were fuselage size and shape, fuselage orientation and proximity to ground, fuselage-opening and location, and wind speed and direction. 79/07/00 79N31175

UTTL: Ignition of fuel sprays by hot surfaces and stabilization of aircraft fires

AUTH: A/SKIFSTD, J. G.; B/LEFEBVRE, A. H.; C/BALLAL, D. R. ; D/SARSTEDER, K. R.; E/KELLY, M. S. CORP: Purdue Univ., Lafayette, Ind. CSS: (School of Mechanical Engineering.)

ABS: This first annual report discusses a research project undertaken to investigate experimentally and theoretically the ignition of fuel sprays by hot surfaces and the stabilization of aircraft fires related to aircraft fire safety. The basic problems are outlined, and the experimental facilities developed for the research are described, along with a discussion of operating experience to date.

RPT#: AD-A065153 AFOSR-79-0079TR 78/11/00 79N23181

UTTL: Applicability of fiber optics to aircraft fire detection systems

AUTH: A/MCGUNIGLE, R. D.; B/JACKSON, H. W.; C/BEAVERS, R. R. CORP: HTL Industries, Inc., Santa Ana, Calif. CSS: (K West Div.)

ABS: A review of the state-of-the-art in ultra-violet conducting fiber optics and related system components was conducted with the objective of evaluating their potential applicability to solar blind, UV fire detection systems. From this basis, conceptual systems were developed and analyzed to assess the potential payoff of incorporating optical enhancement to improve the performance, and reduce the initial and life cycle cost, size and weight of such systems, and to effect detector circuit simplification and improvement in system reliability.

RPT#: AD-A063974 HTL-K-WEST-D-1530 AFAPL-TR-78-84 78/10/00 79N22882

UTTL: New agents for the extinguishment of magnesium fires

AUTH: A/LAWRENCE, K. D.; B/WILLIAMS, F. W.; C/GANN, R. G. CORP: Naval Research Lab., Washington, D. C.

ABS: Ground glass powders (frits) have been evaluated as possible suppressants for magnesium fires. Conceptually, these would melt and form a glass coating on the surface of the burning metal, isolating it from the oxygen supply. Some frits containing oxides of magnesium and lithium reacted violently with the burning magnesium. However, several low melting frits proved to be good suppressants and were better than commercial suppressants.

RPT#: AD-A061664 NRL-6180-376-KDL-FWW-NJS CEEDO-TR-78-19 78/04/00 79N19122

UTTL: Development of fire test methods for airplane interior materials

AUTH: A/TUSTIN, E. A. CORP: Boeing Commercial Airplane Co., Seattle, Wash.

ABS: Fire tests were conducted in a 737 airplane fuselage at NASA-JSC to characterize jet fuel fires in open steel pans (simulating post-crash fire sources and a ruptured airplane fuselage) and to characterize fires in some common combustibles (simulating in-flight fire sources). Design post-crash and in-flight fire source selections were based on these data. Large panels of airplane interior materials were exposed to closely-controlled large scale heating simulations of the two design fire sources in a Boeing fire test facility utilizing a surplused 707 fuselage section. Small samples of the same airplane materials were tested by several laboratory fire test methods. Large scale and laboratory scale data were examined for correlative factors. Published data for dangerous hazard levels in a fire environment were used as the basis for developing a method to select the most desirable material where trade-offs in heat, smoke and gaseous toxicant evolution must be considered.

RPT#: NASA-CR-160119 D6-48071 78/10/00 79N19112

UTTL: Static electricity hazards in aircraft fuel systems

AUTH: A/DUKEK, W. G.; B/FERRARO, J. M.; C/TAYLOR, W. F. CORP: Exxon Research and Engineering Co., Linden, N.J.

ABS: Static discharges that occurred during fueling in small-scale test rigs which simulated aircraft fuel tanks containing open-pore polyurethane foam were used to develop design criteria with respect to foam type, inlet configuration, and JP-4 conductivity. Blue polyether foam is more electrostatically active than red polyester foam; sparks can be eliminated only with a multiple orifice inlet and a minimum fuel conductivity level of 50 pS/m, achieved by adding anti-static additive. With red polyester foam, either the multiple orifice inlet or minimum conductivity fuel suppresses static discharges. Spark energies from blue foam or from high velocity single orifice inlets appear to be 10-100 times greater than from red foam or from multiple orifice inlets. Variables such as flow rate, inlet type and exit velocity, metal charge collectors, fuel conductivity, foam dielectric properties, and other non-metallic fuel components were studied. For example, a rubber bladder cell is not significantly different from an empty tank in terms of static discharges. An aluminum mesh substitute for open-pore foam proved to be effective in minimizing static buildup but produced unacceptable metal fragments which acted as charge collectors.

RPT#: AD-A061450 AFAPL-TR-78-56 EXXON/GRUS.1PEB.78 78/08/00 79N17012

UTTL: The correlation of animal response data with the yields of selected thermal decomposition products for typical aircraft interior materials

AUTH: A/SPURGEON, J. C. CORP: National Aviation Facilities Experimental Center, Atlantic City, N. J.

ABS: Seventy-five aircraft interior materials, including panels, fabrics, foams, and thermoplastics were thermally decomposed under conditions of oxidative pyrolysis in a tube furnace. In one experiment, the thermal decomposition products were directed into an animal exposure chamber containing male albino rats. Both times-to-incapacitation and times-to-death were recorded. In a separate experiment, the thermal decomposition products were collected and analyzed for CO, HCN, H2S, HCl, HBr, NO2, SO2, HCHO, and HF yields Multivariate linear regression analysis was used to correlate the times-to-incapacitation with the yields of the nine TDP's.

RPT#: FAA-NA-78-45 FAA-RD-78-131 78/11/00 79N16815

UTTL: Test of crash-resistant fuel system for general aviation aircraft

AUTH: A/PERRELLA, W. M., JR. CORP: National Aviation Facilities Experimental Center, Atlantic City, N. J.

ABS: A significant percentage of general aviation aircraft accidents result in postcrash fires due to the ignition of fuel spillage, often contributing injury or death to the aircraft occupants. Tests were conducted to demonstrate the performance of light-weight, flexible, crash-resistant fuel cells combined with the use of frangible fuel line couplings. Four full-scale crash tests of a typical light twin aircraft were included in these tests. In three tests, the crash-resistant fuel system performed satisfactorily. The fourth and final test, where the lightest weight tanks were used, resulted in tank failures and demonstrated a possible lower strength limit to the tank material.

RPT#: FAA-RD-78-122 FAA-NA-78-48 78/12/00 79N16815

UTTL: Dayton aircraft cabin fire model validation, phase 1

AUTH: A/MACARTHUR, C. D.; B/MYERS, J. F. CORP: Dayton Univ., Ohio. CSS: (Research Inst.)

ABS: Refinements were made to the Dayton University aircraft fire mathematical model following a comparison to seven full-scale cabin mock up fire tests. Changes include a generalization of the treatment of the cabin geometry to include of various widths, improved thermal radiation modeling, computation of oxygen consumption, and a treatment of forced ventilation. A laboratory testing program to acquire flammability, smoke, and gas generation data on the furnishing materials of the full-scale test is described. Based on the results of the comparisons, sections of the mathematical model which require further refinement are identified and some appropriate refinements are suggested.

RPT#: AD-A058547 UDRI-TR-78-44 FAA-RD-78-57 78/03/00 79N12050

UTTL: Douglas Aircraft cabin fire tests

AUTH: A/KLINCK, D. CORP: Douglas Aircraft Co., Inc., Long Beach, Calif. In NASA. Ames Res. Center Conf. on Fire Resistant Mater. (FIREMEN) p 39-68 (SEE N79-12029 03-03)

ABS: Program objectives are outlined as follows: (1) examine the thermal and environmental characteristics of three types of fuels burned in two quantities contained within a metal lavatory: (2) determine the hazard experienced in opening the door of a lavatory containing a developed fire; (3) select the most severe source fuel for use in a baseline test; and (4) evaluate the effect of the most severe source upon a lavatory constructed of contemporary materials. All test were conducted in the Douglas Cabin Fire Simulator. 78/10/00 79N12031

UTTL: Conference on Fire Resistant Materials (FIREMEN): A compilation of presentations and papers

AUTH: A/KOURTIDES, D. A. CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. Conf. held at Ames Res. Center, Moffett Field, Calif., 13-14 Apr. 1978

RPT#: NASA-TM-78523 A-7605 78/10/00 79N12029

UTTL: Tests of crash-resistant fuel system for general aviation

AUTH: A/PERRELLA, W. M., JR. CORP: National Aviation Facilities Experimental Center, Atlantic City, N. J.

ABS: A significant percentage of general aviation aircraft accidents result in post-crash fires due to the ignition of fuel spillage, often contributing injury or death to the aircraft occupants. Testing was performed to demonstrate the performance of light-weight, flexible, crash-resistant fuel cells combined with the use of frangible fuel line couplings. Included in these tests were three full-scale crash tests of a typical light twin aircraft. In all of these tests, the crash-resistant fuel system performed satisfactorily.

RPT#: AD-A054141 FAA-NA-77-48 FAA-RD-78-28 78/03/00 78N28081

UTTL: Fire fighter tools
AUTH: A/KNOWLES, N. D. CORP: Civil and Environmental Engineering Development Office, Tyndall AFB, Fla.
ABS: The Civil and Environmental Engineering Development Office (CEEDO) conducted an evaluation of aircraft crash rescue/fire fighters tools and equipment. This study was necessitated due to the continued growth and development of new tools and the ever increasing numbers of tools being acquired by Air Force Fire Protection Organizations. The purpose of the study was to verify the concepts for fire fighting and rescue operations; to identify the tools and equipment presently carried on fire fighting and rescue vehicles; to determine the usefulness of all inventoried tools and equipment; and to determine a basic selection of tools and equipment that should be carried on fire fighting and rescue vehicles.
RPT#: AD-A051687 CEEDO-TR-78-2 78/01/00 78N23107

UTTL: Time-dependent fire behavior of aircraft cabin materials
AUTH: A/HUGGETT, C. CORP: National Bureau of Standards, Washington, D.C. CSS: (Center for Fire Research.)
ABS: In an aircraft cabin or other inhabited compartment, the early stages of fire growth are critical to life safety. During this period the rate of fire growth, as measured by the mass fuel consumption rate, can be represented approximately as a simple exponential function of time. The rates of development of hazard from temperature rise and smoke and gas accumulation can be related to the mass fuel consumption rate. The growth constant k can be related to a small number of system parameters and fuel combustion properties. These properties were identified and laboratory methods for their measurement are suggested. In a fire situation, the critical hazard (temperature, smoke or gas) can be considered to be the one which first reaches a limiting human tolerance level. This mode can be identified and the effects of changes in design and materials on the rate of critical hazard development can be estimated. The simple exponential growth model may provide a means of predicting relative hazard with reasonable accuracy.
RPT#: AD-A050923 FAA-RD-77-99 77/12/00 78N21234

UTTL: Studies of the flash fire potential of aircraft cabin interior materials
AUTH: A/MANKA, M. J.; B/PIERCE, H.; C/HUGGETT, C. CORP: National Bureau of Standards, Washington, D.C.; National Aviation Facilities Experimental Center, Atlantic City, N. J.
ABS: A minimum energy principle was proposed to characterize the flash fire behavior of the complex mixture of fuels derived from the pyrolysis of organic materials. This principle states that a flash fire is possible when the potential combustion energy content of the pyrolyzate air mixture exceeds approximately 425 cal/L. A variety of experiments was performed to provide support for the minimum energy principle. The results were in general agreement with predictions, but the accuracy of the measurements was not good enough to permit detailed conclusions. Oxidative pyrolysis plays a significant role in the formation of the fuel-air mixture in the flash fire cell. Particulates contribute to the creation of flash fire conditions, but they present a difficult measurement problem.
RPT#: AD-A048475 NA-77-180 FAA-RD-77-47 77/12/00 78N18158

UTTL: An investigation of lightning damage to nonmetallic composite aircraft materials and associated protective systems
AUTH: A/LORENZ, S. A. CORP: Kansas Univ., Lawrence.
ABS: The inherent dangers of operating aircraft equipped with nonmetallic components within the natural lightning environment are described. A philosophy for simulating the natural lightning current waveform is presented and a circuit to produce simulated waveforms is proposed. A chronicle of the design construction, and operation of a simulation facility based on this circuit, is presented with emphasis on design and operational safety aspects. A test program using boron/epoxy and graphite/epoxy material specimens is outlined. Possible applications and modifications for this type of facility are suggested that are commensurate with the future uses of nonmetallic composite materials in aircraft structures. 77/00/00 78N17292

UTTL: Characterization of secondary ignition sources in unattended compartments and full-scale baseline test
AUTH: A/KLINK, D. M. CORP: Douglas Aircraft Co., Inc., Long Beach, Calif.
ABS: The characteristics of five fuel loads burned within a metal lavatory were identified. In 15 of the tests the lavatory door remained closed for the 30-minute test period while in 15 additional tests the door was opened after the fire had developed. Upon completion of these tests the most severe source was selected for use in the baseline test. In the baseline test, the lavatory and adjacent panels, all of which were constructed of contemporary materials, were tested for

a period of 1 hour. Thermal, environmental, and biological data were obtained for all fuel loads, door conditions, and the baseline test. All tests were conducted in a cabin fire simulator with separate ventilation of the cabin and lavatory representative of an inflight condition. The baseline test established that by using the most severe fuel source (1) the exposed animal subject survived without complications; (2) no toxic levels of gas within the cabin were detected; (3) a propagating fire did not develop in adjacent structures; (4) the lavatory containing the fire remained structurally intact; (5) decomposition of portions of the lavatory did occur; and (6) cabin visibility would have presented a problem after 5 minutes.

RPT#: NASA-CR-151573 JSC-13792 77/11/00 78N13028

UTTL: Full-scale aircraft crash tests of modified jet fuel

AUTH: A/AHLERS, R. H. CORP: National Aviation Facilities Experimental Center, Atlantic City, N. J.

ABS: Crash tests were conducted with two A3 and two RB66 aircraft under impact-survivable crash conditions. The wing tanks in the first RB66 aircraft contained Jet A fuel modified with an 0.7-percent polymeric additive. The aircraft was crash tested into the specially constructed test site at 104.6 knots. The fuel mist generated by the fuel released from four crash-inflicted openings in the front wing spar was not ignited by the array of ignition sources. The wing tanks in the second RB65 aircraft were filled with JET A fuel modified with 0.5-percent of the same polymeric additive. The aircraft was crashed into the test site at 102.4 knots. The test conditions for the second RB66 test were made more severe by increasing the fuel temperature, partially drilling out areas in the front spar to increase the opened fuel spillage area, and by adding four fuel release openings under the wing, larger ignition sources, and operating the engines. The fuel mist burst into flame and followed the aircraft down the test site, continuing to burn until extinguished by the firefighting crew. These full-scale tests indicate that modified fuels have a potential for reducing the postcrash fire hazard.

RPT#: AD-A043843 FAA-NA-77-35 FAA-RD-77-13 77/07/00 78N11251

UTTL: Design of a cascade fire apparatus for testing countermeasure effectiveness

AUTH: A/WIERSMA, S.; B/ALGER, R. S.; C/MCKEE, R. G.; D/JOHNSON, W. H. CORP: DOD Aircraft Ground Fire Suppression and Rescue Office, Wright-Patterson AFB, Ohio.

ABS: A cascade fire apparatus was designed to be used in the evaluation of agent effectiveness and application techniques in suppressing accidental aircraft ground fires involving fuels which are cascading, spraying, or pouring. The apparatus provides for (1) a controllable burning rate, (2) a reproducible fire, (3) a flame geometry that minimizes wind effects, and (4) an adjustable size by virtue of its modular nature. One of the two fuel supply nozzling options yields a smokeless fire; however, the other option has better fire characteristics for evaluating some of the countermeasures. Suppression tests were conducted using PKP and Monnex dry chemical agents and gaseous Halon 1211. It was not possible to compare the effectiveness of Halon 1211 and the powder agents because of the different application rates and capacities of the extinguishers tested and, therefore, the different required fire size. The apparatus appeared to be well suited for evaluation of agent effectiveness against the kinematic fires and also for training firemen in fighting these fires.

RPT#: AD-A043176 DOD-AGFSRS-76-7 76/06/00 77N32101

UTTL: US air carrier accidents involving fire, 1965 through 1974 and factors affecting the statistics

CORP: National Transportation Safety Board, Washington, D. C. CSS: (Bureau of Technology.)

ABS: Statistical data on U.S. air carrier accidents involving fire from 1965 through 1974 are compared with similar data for the preceeding decade. While fire still occurs in about 20 percent of the accidents in scheduled passenger operations, the ratio of fatalities from all causes to exposed occupants declined 65 percent in this study period and the ratio of fatalities from the effects of fire and smoke to exposed occupants declined 37 percent. The almost exclusive use, in this study period, of turbojet-powered aircraft, their improved reliability, and the use of kerosene-type fuel are factors influencing the statistics.

RPT#: P3-266883/8 NTSB-AAS-77-1 77/02/17 77N31112

UTTL: Aircraft accident report. Air Chicago Freight Airlines, Inc., North American TB-25n, n94462, Midway Airport, Chicago, Illinois, August 6, 1976 CORP: National Transportation Safety Board, Washington, D. C. CSS: (Bureau of Accident Investigation.)

ABS: On August 6, 1976, N9446Z crashed while attempting an emergency landing at Midway Airport, Chicago. The left engine failed during climbout from Midway Airport, which precipitated an uncontrollable engine fire. The probable cause of the accident was the deterioration of the cockpit environment, due to smoke to the extent that the crew could not function effectively in controlling the aircraft under emergency conditions. The smoke and fire, originating from a massive failure in the power section of the left engine, propagated into the bomb bay area and then into the cockpit. The inspection system utilized was not effective in detecting the impending engine failure.

RPT#: NTISUB/C/104-003 NTSB-AAR-77-3 77/04/14 77N30792

UTTL: Aircraft fire simulator testing of candidate fire barrier systems

AUTH: A/HOFFMAN, H. H.; B/FONTENOT J. S. CORP: Naval Weapons Center, China Lake, Calif.

ABS: The results of a study to evaluate candidate aircraft fire barrier materials to in-flight fires are presented. Four organic materials, two inorganic materials, and three metallics combined with insulators were tested in an in-flight fire simulator. Eight intumescent coatings were evaluated to determine their ability to close barrier gaps in the event of a fire.

RPT#: AD-A038601 NWC-TP-5915 76/11/00 77N28102

UTTL: Evaluation of a Halon 1301 system for aircraft internal protection from a postcrash external fuel fire

AUTH: A/HILL, R. CORP: National Aviation Facilities Experimental Center, Atlantic City, N. J.

ABS: The use of a Halon 1301 fire suppression system was evaluated in regard to increasing occupant escape time during a ground crash situation with an external fire adjacent to a cabin opening. Tests were conducted in a DC7 fuselage, varying the exit configurations and external wind conditions. Tests were also conducted using a curtain to compartmentize the cabin, with the Halon 1301 concentration and location of discharge being varied. Smoke, temperature, carbon monoxide, oxygen, and Halon 1301 levels were continuously monitored during the tests at various locations throughout the cabin. Hydrogen fluoride (HF) and hydrogen bromide (HBr) concentrations were obtained by analyzing samples taken from the cabin at various times. The results indicated that the length of protection from flame penetration through an opening was dependent upon external wind conditions. Flame penetration was controlled for up to 3.5 minutes with zero wind, but with a wind of as little as 2 miles per hour (mi/h), the time was reduced to less than 15 seconds. HF levels were rapidly reached inside the cabin, with concentrations ranging from 60 parts per million (p/m), with no wind, to well over 300 p/m with 2-mi/h wind conditions.

RPT#: AD-A039056 FAA-NA-76-42 FAA-RD-76-218 77/03/00 77N27085

UTTL: Void filler foam accelerated load testing

AUTH: A/BURT, W. T. CORP: Naval Weapons Center, China Lake, Calif.

ABS: This report presents the Phase IV program to qualify void filler foam for use in military aircraft. Phases I, II, and III of this task also are summarized in this report to show the evolution of the void filler foam concept. The purpose of the foam installation around the aircraft fuel cell is to reduce projectile damage and fuel fire hazard, and to improve thermal protection and aircraft survivability. The accelerated load testing was conducted to determine the ability of void filler foam to withstand the loads encountered during aircraft carrier deck operations. Results of the program show the void filler foam, used as a replacement for the backingboard on an A-4 aircraft, can withstand the loads associated with catapult launch and arrested landings.

RPT#: AD-A034118 JTCG/AS-74-T-011 76/11/00 77N23273

UTTL: Effectiveness of smoke abated training in simulated crash fire fighting

AUTH: A/DALLMAN, B. E.; B/DELEO, P. J. CORP: Air Force Human Resources Lab., Brooks AFB, Tex.

ABS: Concern for the environment has resulted in the development of a water spray apparatus which can greatly reduce the smoke associated with aircraft crash fire simulations used in fire fighter training. This study compared the effectiveness of smoke abated training with conventional procedures. Results showed no significant differences between students trained under smoke abated conditions and those who experienced natural, or smoky, fires during training. However, students who had received smoke abated training were less confident and more unsure of the effectiveness of their training than conventional students. It was concluded that smoke abated training can be an effective method for training fire

protection specialists with certain constraints. Recommendations regarding employment of the smoke suppression apparatus are provided in the report.
RPT#: AD-A034843 AFHRL-TR-76-60 76/08/00 77N23078

UTTL: Aviation safety. Volume 2: Aircraft cabin environment CORP: Committee on Public Works and Transportation (U. S. House). GPO Hearings before Subcomm. on Investigations and Review of Comm. on Public Works and Transportation, 94th Congr., 2d Sess., 3-5 Feb. 1976
ABS: Cabin safety problems and potentially dangerous passenger environment conditions are discussed with emphasis on the seating and safety of flight attendants. Topics explored include oxygen mask testing, smoke hoods, the use of china dishes and carts, and the serving of alcoholic beverages.
RPT#: GPO-70-797 76/00/00 77N22053

UTTL: Aircraft cabin compartmentation concepts for improving postcrash fire safety
AUTH: A/HILL, R.; B/BORIS, P. N.; C/JOHNSON, G. R. CORP National Aviation Facilities Experimental Center, Atlantic City, N. J.
ABS: Aircraft cabin compartmentation was investigated as a means of increasing escape time for passengers during a postcrash cabin fire. The size and configuration of various partitions and/or curtains were investigated to determine their effectiveness in providing protection from a cabin fire by limiting the spread of heat, smoke, carbon monoxide (CO), and the depletion of oxygen from the vicinity of the fire to other areas of the cabin. The results of these tests indicate that a tightly sealed partition and/or curtain afforded the greatest protection from the spread of a given amount of heat, CO, and depletion of oxygen. The results also indicated that the use of compartmentation can adversely affect the intensity of a fire in an unclosed area, creating more products of combustion. Except for a limited number of cases, the amount of protection provided by the partition exceeded the increase in fire intensity.
RPT#: AD-A033051/4 FAA-NA-76-12 FAA-RD-76-131 76/10/00 77N20053

UTTL: Aircraft operational experience and its impact on safety and survivability CORP: Advisory Group for Aerospace Research and Development, Paris (France). Presented at the Flight Mech. Panel Symp., Sandefjord, Norway, 31 May - 3 Jun. 1976
RPT#: AGARD-CP-212 AD-A037402 77/01/00 77N19031

UTTL: Recent experiment/advances in aviation pathology CORP: Advisory Group for Aerospace Research and Development, Paris (France). Presented at the Aerospace Med. Panel Specialists' Meeting, Copenhagen, 5-9 Apr. 1976
RPT#: AGARD-CP-190 ISBN-92-835-0184-5 AD-A036347 76/12/00 77N17710

UTTL: Structural response of fluid containing tanks to penetrating projectiles (hydraulic ram): A comparison of experimental and analytical results
AUTH: A/BALL, R. E. CORP: Naval Postgraduate School, Monterey, Calif.
ABS: This report presents the results of a study of (1) the fluid hydraulic ram pressures in a fluid-containing-tank caused by a penetrating projectile, and (2) the transient response of the entry and exit walls of the tank due to the fluid pressure. The experimental and analytical hydraulic ram and structural response programs at the Naval Weapons Center (NWC) and the Naval Postgraduate School (NPS) are briefly described. The computer analyses for the fluid pressure at the entry and exit walls and the transient entry and exit wall strains are described in detail. Comparisons are made of the predicted wall strains with the circular entry wall strains, measured at NPS, and the square exit wall strains, measured at NWC. Good agreement in the form of the strain histories is obtained, but the magnitudes of the predicted strains are smaller than those of the measured strains. This study contributes to the knowledge of the hydraulic ram phenomenon and associated fluid-structure interaction, and should provide some useful information for the design of aircraft fuel tanks.
RPT#: AD-A026320 NPS-57BP76051 76/05/00 77N15466

UTTL: Environmental degradation of fuels, fluids and related materials for aircraft
AUTH: A/HODGSON, F. N.; B/KEMMER, A. M. CORP: Monsanto Research Corp., Dayton, Ohio. CSS: (Dayton Lab.)
ABS: Investigations of the composition and properties of a number of hydrocarbon fuels are described. Fuel analyses for hydrocarbon types, trace metals content, trace organic contaminants and elemental composition are presented. Studies of the fluorescence spectral properties of aircraft exhaust emissions are described, as is an investigation of the feasibility of using fluorometric measurements on fuels to supplement coker thermal stability data. An investigation of the experimental parameters of the hot manifold flammability test is discussed along with

test results for various hydraulic fluids. Components recovered from aircraft crash sites have been examined to determine factors contributing to aircraft failure Studies supporting Air Force programs for the formulation and specification development of high density fuels are presented.

RPT#: AD-A026908 MRC-DA-539 AFAPL-TR-76-26 76/03/00 77N15214

UTTL: Conference on the Development of Fire-Resistant Aircraft Passenger Seats

AUTH: A/FEWELL, L. L.; B/KOURTIDES, D. A.; C/ROSSER, R. W ; D/PARKER, J. A. CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. Conf. held at Moffett Field, Calif., 19 Mar. 1976

ABS: Papers are presented dealing with the development of aircraft seats with the minimum fire risk. Criteria examined include: flame spread, heat release, and smoke and/or toxic fumes. Materials and performance specifications of all seat material options are provided.

RPT#: NASA-TM-X-73144 A-6633 76/08/00 77N11111

UTTL: Aircraft ground fire suppression and rescue systems. Characteristics of kinematic jet fuel fires cascading and rod fuel geometries

AUTH: A/ALGER, R. S.; B/LAUGHRIDGE, F. I.; C/WILTSHIRE, L L.; D/MCKEE, R. G.; E/JOHNSON, W. H.; F/ALVARES, N S. PAA: D/(Stanford Res. Inst., Menlo Park, Calif.) E/(Stanford Res. Inst., Menlo Park, Calif.); F/(Stanford Res. Inst., Menlo Park, Calif.) CORP: Naval Surface Weapons Center, White Oak, Md.; Stanford Research Inst., Menlo Park, Calif. DON Aircraft Ground Fire Suppression and Rescue Office

ABS: Based on a survey of kinematic fuel fires in aircraft accidents, two types, i.e., cascade and rod fuel flows, were selected to theoretical and experimental examination. The twofold objectives was (1) relate fire characteristics such as burning rate, radiation field, and flame size to the fuel parameters, the flowing conditions, and the environment, and (2) determine the parameters and their degree of control required to achieve reproducible fires suitable for testing extinguishing agents, equipment, and techniques. Theoretical models based on steady, laminar, one-dimensional flow were developed.

RPT#: AD-A024447 DOD-AGFSRS-76 3 76/03/00 77N11022

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-LS-123	ISBN 92-835-1424-6	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title

AIRCRAFT FIRE SAFETY

7. Presented at a Lecture Series under the sponsorship of the Propulsion and Energetics Panel and the Consultant and Exchange Programme of AGARD, on 7–8 June 1982 in Oslo, Norway, on 10–11 June 1982 in London, UK and on 15–16 June 1982 in Washington D.C., USA.

8. Author(s)/Editor(s)	9. Date
Various	May 1982

10. Author's/Editor's Address	11. Pages
Various	180

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Fire safety
Aircraft fires
Aviation accidents
Aviation safety
Aviation personnel
Survival
Human behaviour

14. Abstract

The Lecture Series was based on the results of the AGARD PEP Working Group 11, on the same subject. The results were published in the AGARD Advisory Report No.132, Volumes I and II. In the presentations, the results were updated and concentrated on the enhancement of passenger and crew fire survivability under aircraft crash conditions. The survivability represents the highest priority of fire safety needs.

The contents covered:

- Aircraft Mishap Experience with respect to Definition of Post Crash Fire Scenario/Survivability Factors
- Availability and Operational Suitability of Aviation Fuels versus Fire Safety Enhancement
- Applicability of Aircraft Subsystems Fire Protection Engineering Techniques for Enhancement of Post Crash Fire Survivability
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- Aircraft Post Crash Survivability – Human Response Factors – Physiological, and Psychological.

AGARD Lecture Series No.123
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180 pages

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ISBN 92-835-1424-6

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Printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London W1P 1HD

ISBN 92-835-1424-6